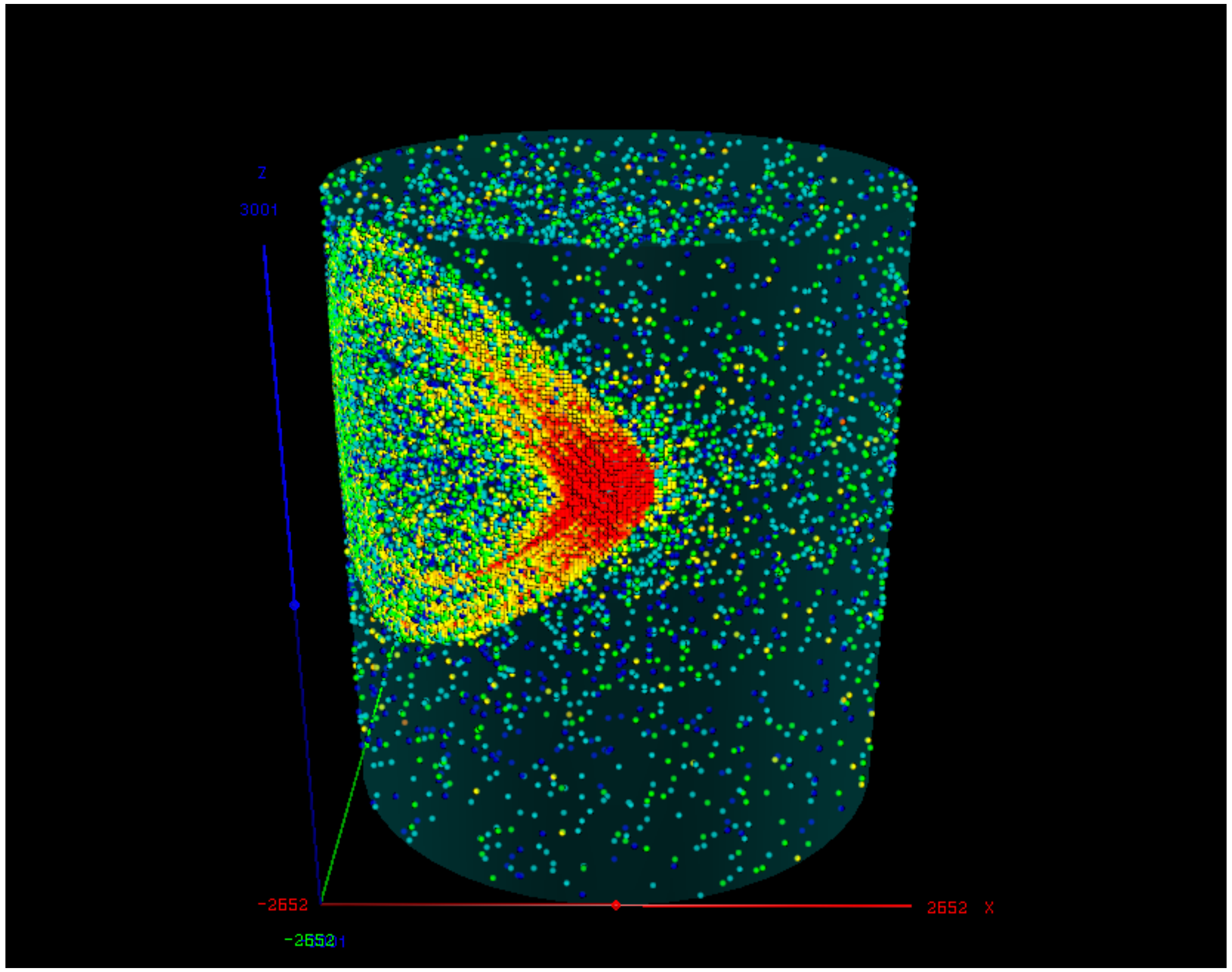
DM@LBNE



Chris Jackson (UTA)

in collaboration with B. Batell and, oh yeah, some experimentalists ;)
(A. Farbin, S. Shahsavarani and J. Yu)

Preface

- Like many of the highways in the Chicagoland area, the study described in this talk is (just) under construction… i.e., it's a "work in progress"

- We're in the "first stages" of this work (by far, not the last word… and things I say could even be just flat out wrong ;)

- We welcome any and all comments and suggestions.

- In what follows, I will explain what we have done (just in the past few weeks) and what we envision for the road ahead (pun intended).

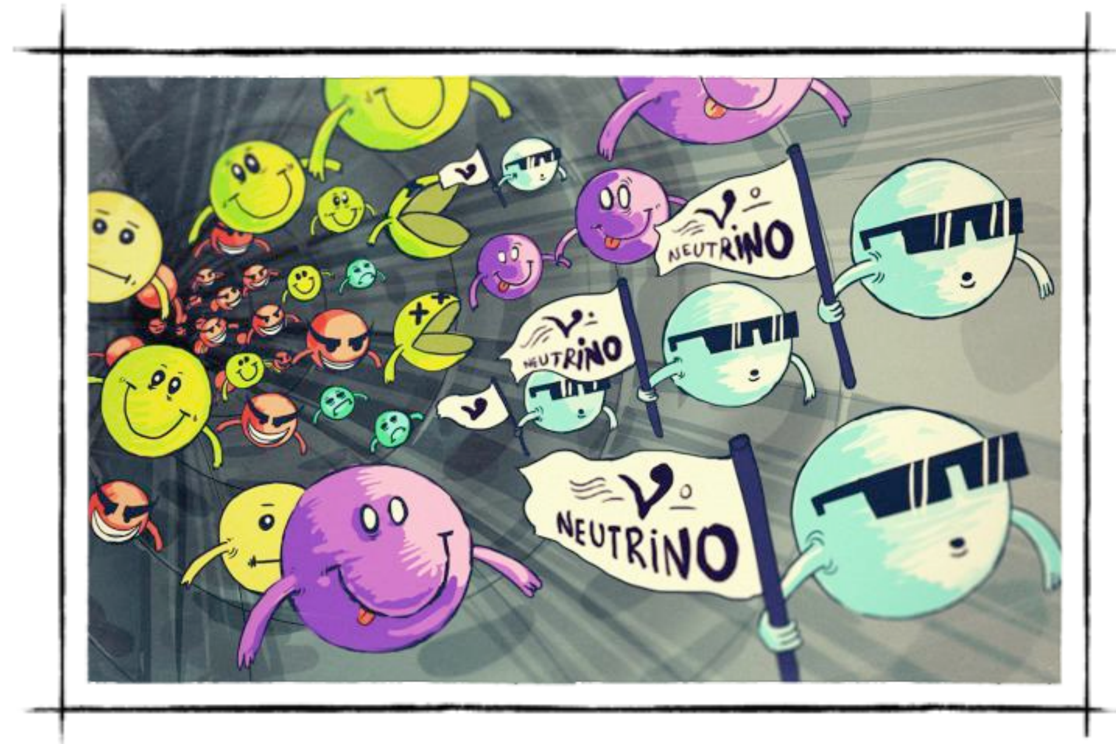
Goals of this Study

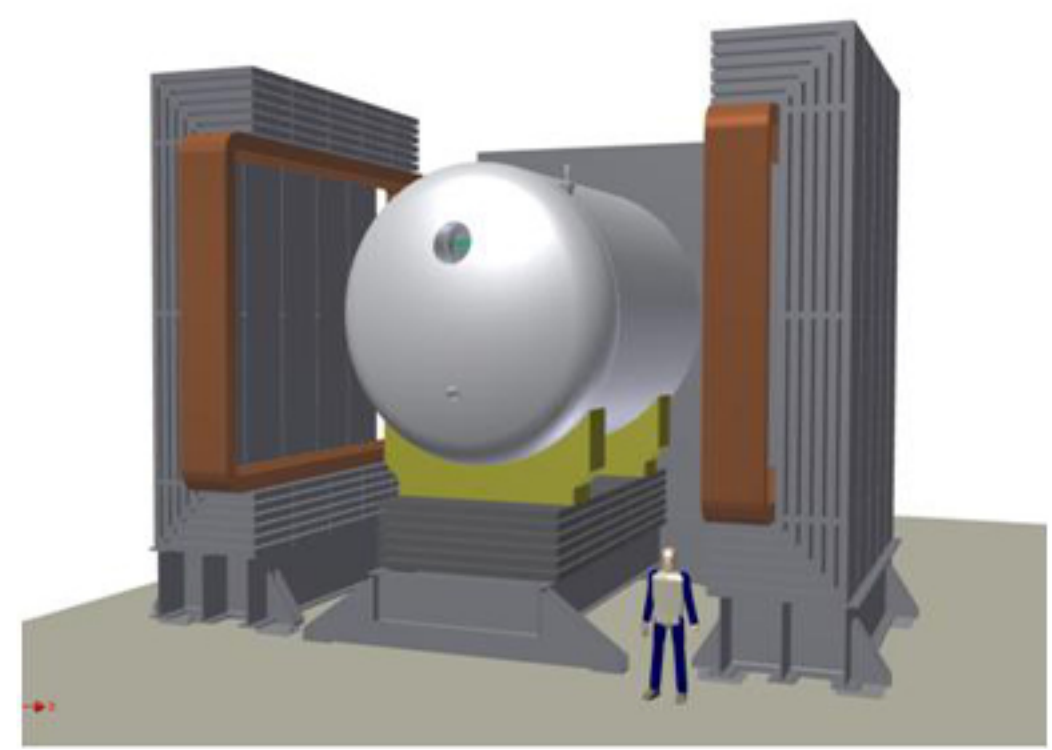
- Study the possibility (or feasibility) of detecting and studying light (sub-GeV) dark matter at the “Long Baseline Neutrino Experiment” (LBNE)

- Perform this study in a model-independent manner… or at least (eventually) study as many models as humanly-possible.

- Use the results of this study to help influence the technology behind a near detector at LBNE and its placement

- Long-term: build a generic MC event generator for dark matter production at fixed-target experiments (something like GENIE)





So much for model-independence…

- As a first step towards a model-independent study… we need to choose a model (as a case study)

- For simplicity/transparency, we choose the U(1)′ "vector portal" model:

$$\mathcal{L}_{mix} = \frac{\epsilon}{2} F^{\mu\nu} V_{\mu\nu}$$

  with Dirac fermion dark matter (χ):

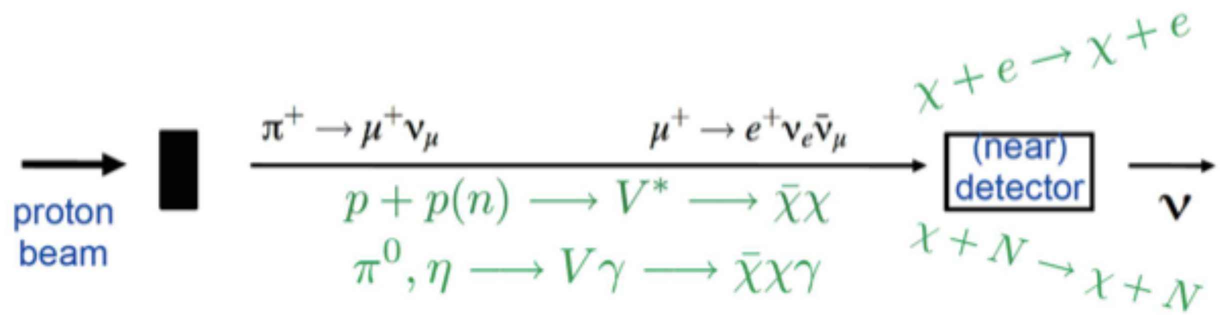
$$\mathcal{L}_V = V_\mu \left(e\epsilon J^\mu_{em} + e' J^\mu_\chi \right)$$

- In general, this extension of the SM has four free parameters: two couplings (ϵ and α') and two masses (m_V and m_χ).

- This model has been well-studied and relatively strong limits have been placed on these parameters from collider and cosmological data. For the time being, though, *we choose to ignore these constraints* ;)

Production of Vector Portal DM @ FT Experiments

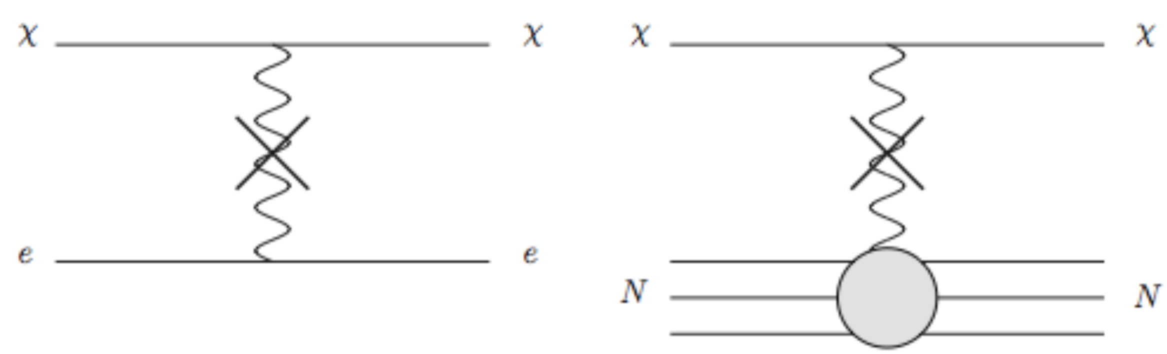
- How could we produce this type of DM at fixed-target experiments?



Note: production of ν's occurs all the way down the beam pipe… whereas DM production occurs only at the target.

- The production sub-processes:

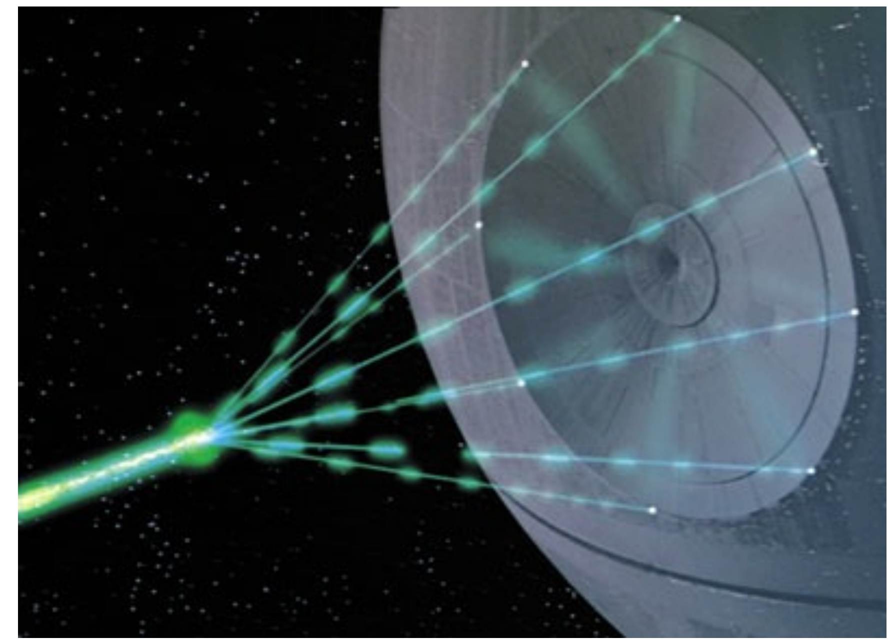
- Detection:



Production of Vector Portal DM @ LBNE

- At the "BooNE" experiments, the energy of the proton beam (~ 8 GeV) limits production of DM to the indirect π^0,η decay channels.

Main injector proton beam



- LBNE will make use of the main injector proton beam (~ 120 GeV) and should allow us to probe the direct production mode.

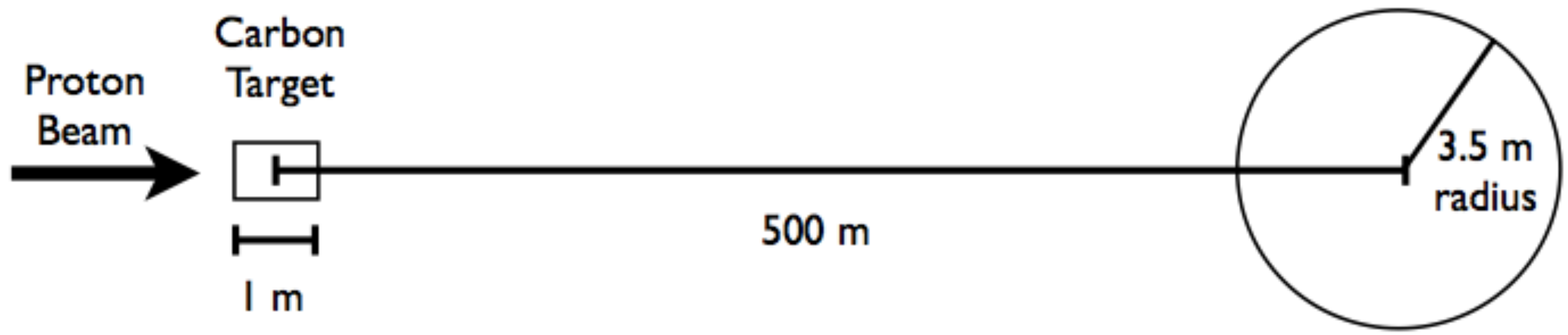
- DM particles will be highly boosted, so the hope is that their effects on the scattered electrons/nuclei will be distinguishable from those of neutrinos.

- In order to perform this study, a "near" detector will be required. The flux of DM particles at the "far" detector (either on the surface or underground) will just be too small.

- Unfortunately, at this time, a "near" detector isn't "on the books." We hope our study (and the importance of having an ND for neutrino physics) will make a difference in the cause.

Our Setup

- We generate 1 million DM events using Madgraph5 (in “FT mode”) and idealize the LBNE setup as:



- For the accelerator, target and detector specs, we use:

$N_{POT} = 3 \times 10^{21}$ (number of protons on target)

$n_T = 10^{23}$ (number density of carbon atoms in the target)

$L_T = 100$ cm (length of target)

$\text{Theta}_{det} = 3.5\text{m}/500\text{m} = 0.007 = 0.4$ degrees (angular acceptance)

$n_D = 5 \times 10^{23}$ (number density of electrons in detector)

$R_D = 350$ cm (radius of detector)

$d = 500$ m (distance from target to detector)

- We consider two benchmark points: (m_X, m_V) = (300 MeV, 1 GeV) and (1 GeV, 3 GeV)

- Neutrino events are simulated by our experimental friends

Signal Rate Estimate

- How many DM particles could we possibly detect?

$$N_{event} = N_{POT} n_T L_T \left(12\, \sigma_{pp \to \chi\bar{\chi}}\right) n_D R_D \sigma_{\chi e} \times \eta_{det}$$ (η_{det} = 0.042 %)

- The cross sections are approximately:

$$\sigma_{pp \to \chi\bar{\chi}} \simeq 10^7 \text{ pb} = 10^{-29} \text{ cm}^2$$ (madgraph)

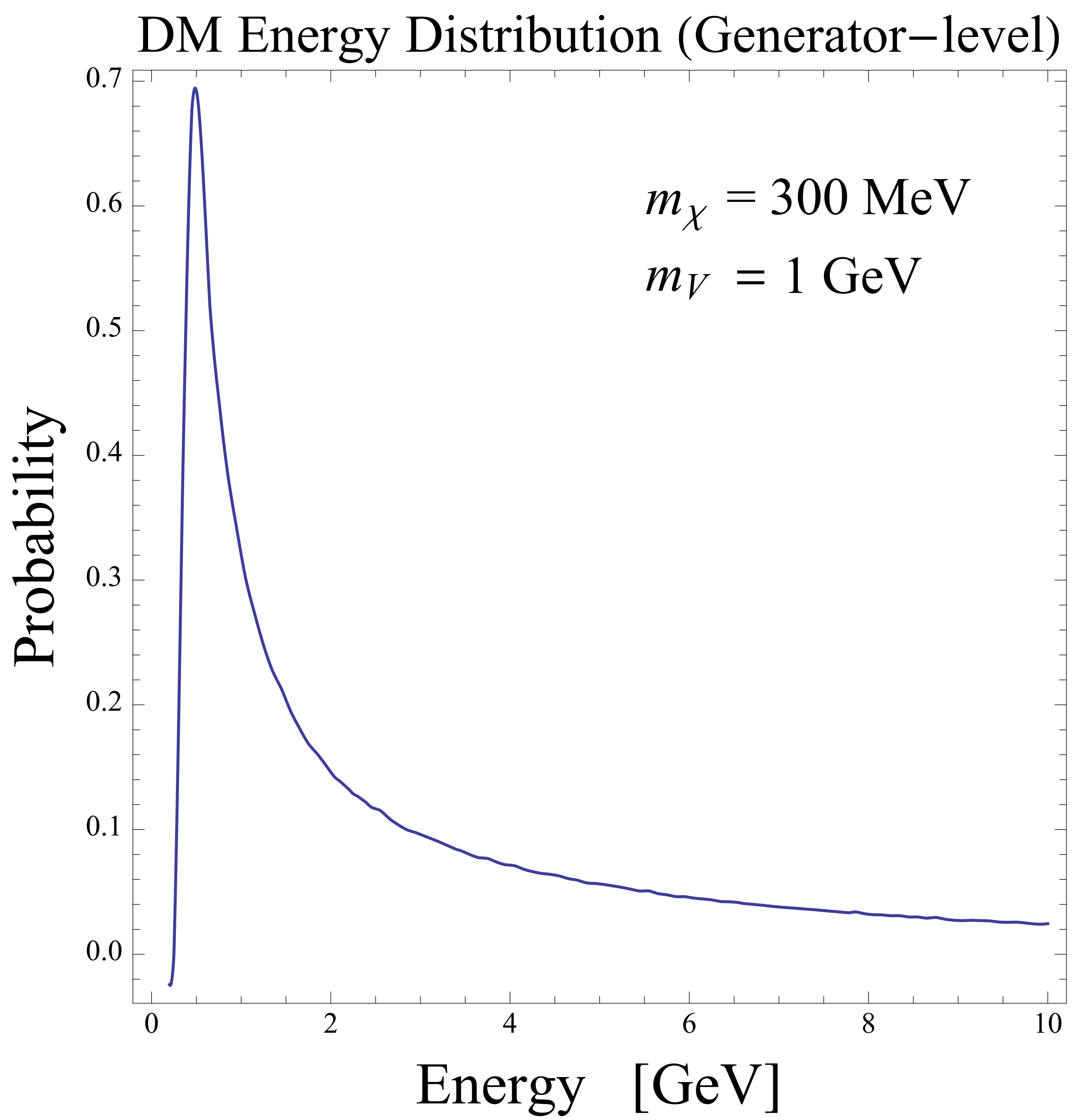
$$\sigma_{\chi e} \simeq 10^{-32} \text{ cm}^2$$ (analytic)

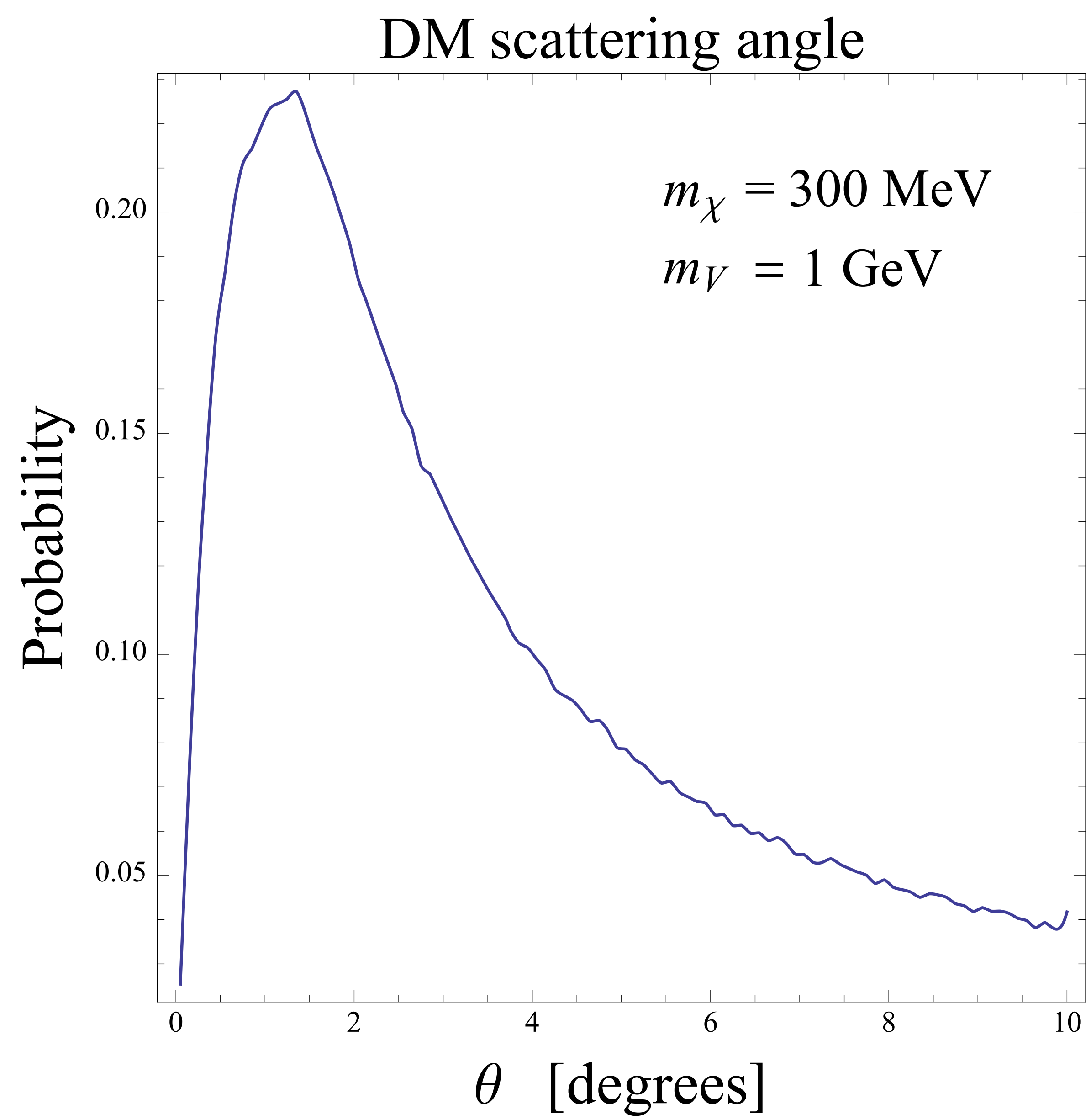
- Plugging in the numbers from the previous slide:

$$N_{event} \approx 10^{10} \times \epsilon^4 \left(\frac{\alpha_D}{0.1}\right)^2$$

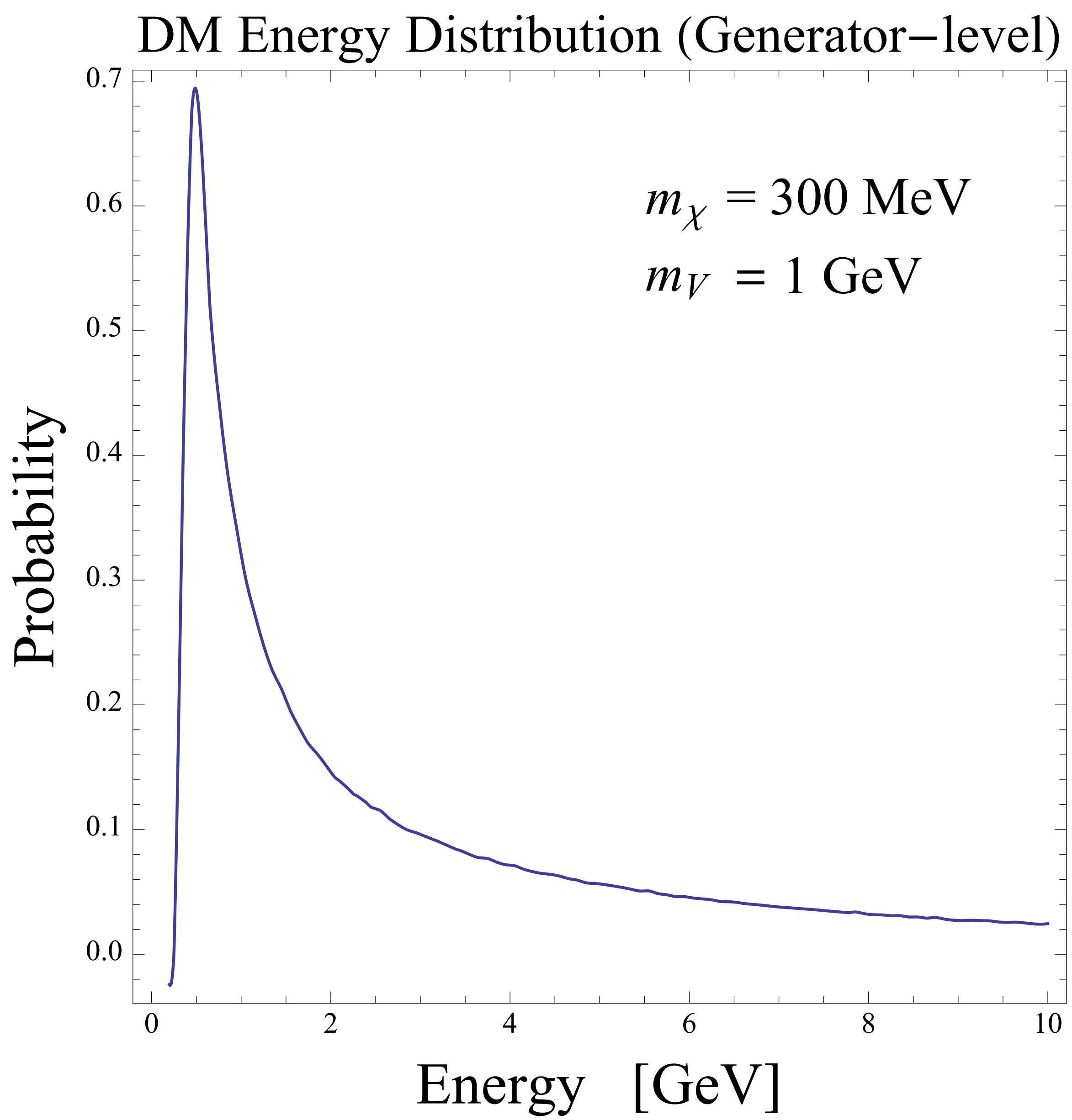
- Plenty of signal events to constrain the model parameter space (provided we can deal with the pesky neutrino background). Possible to probe $\epsilon \approx 10^{-2}$ - 10^{-3}(?)

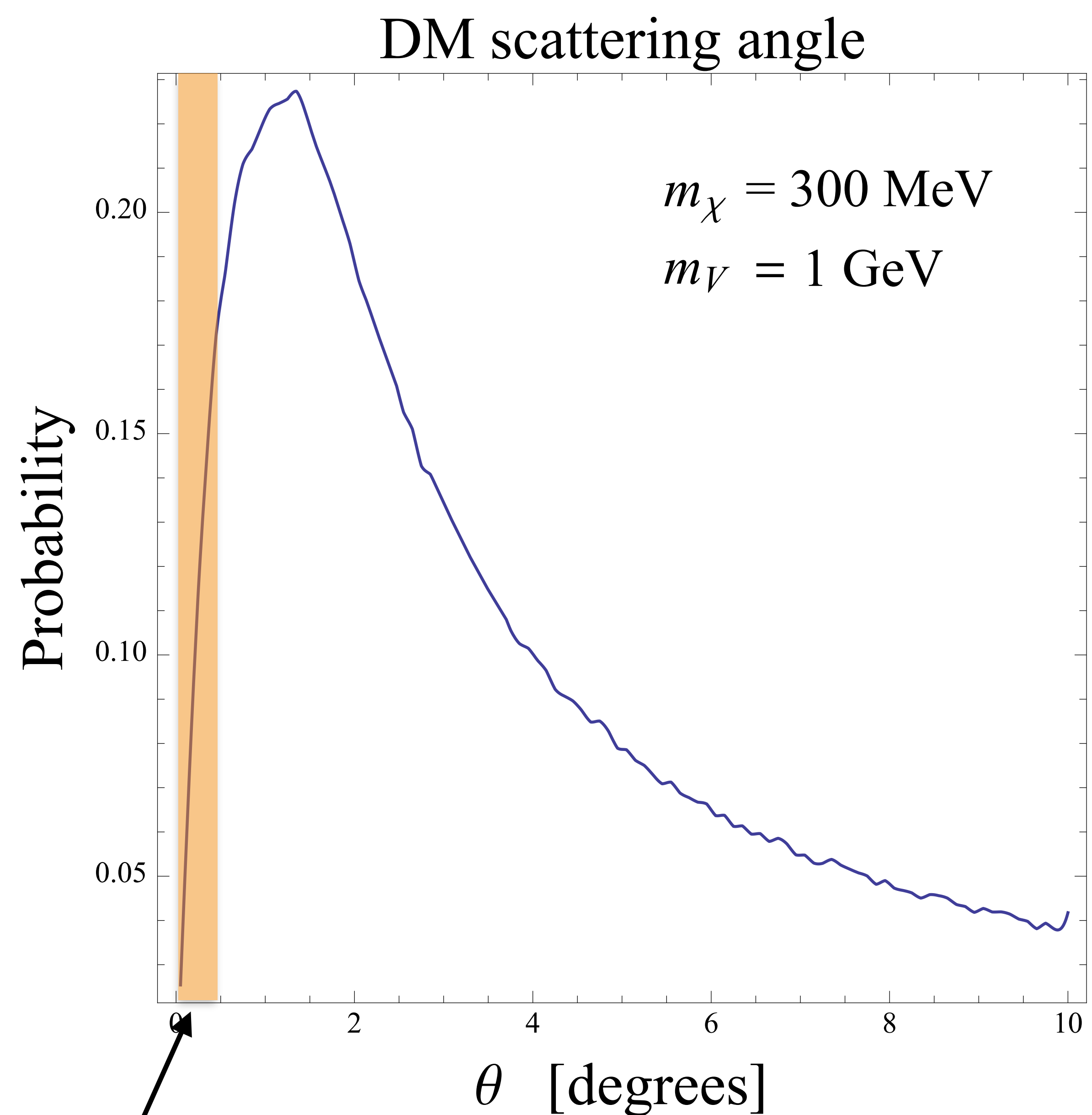
DM Production





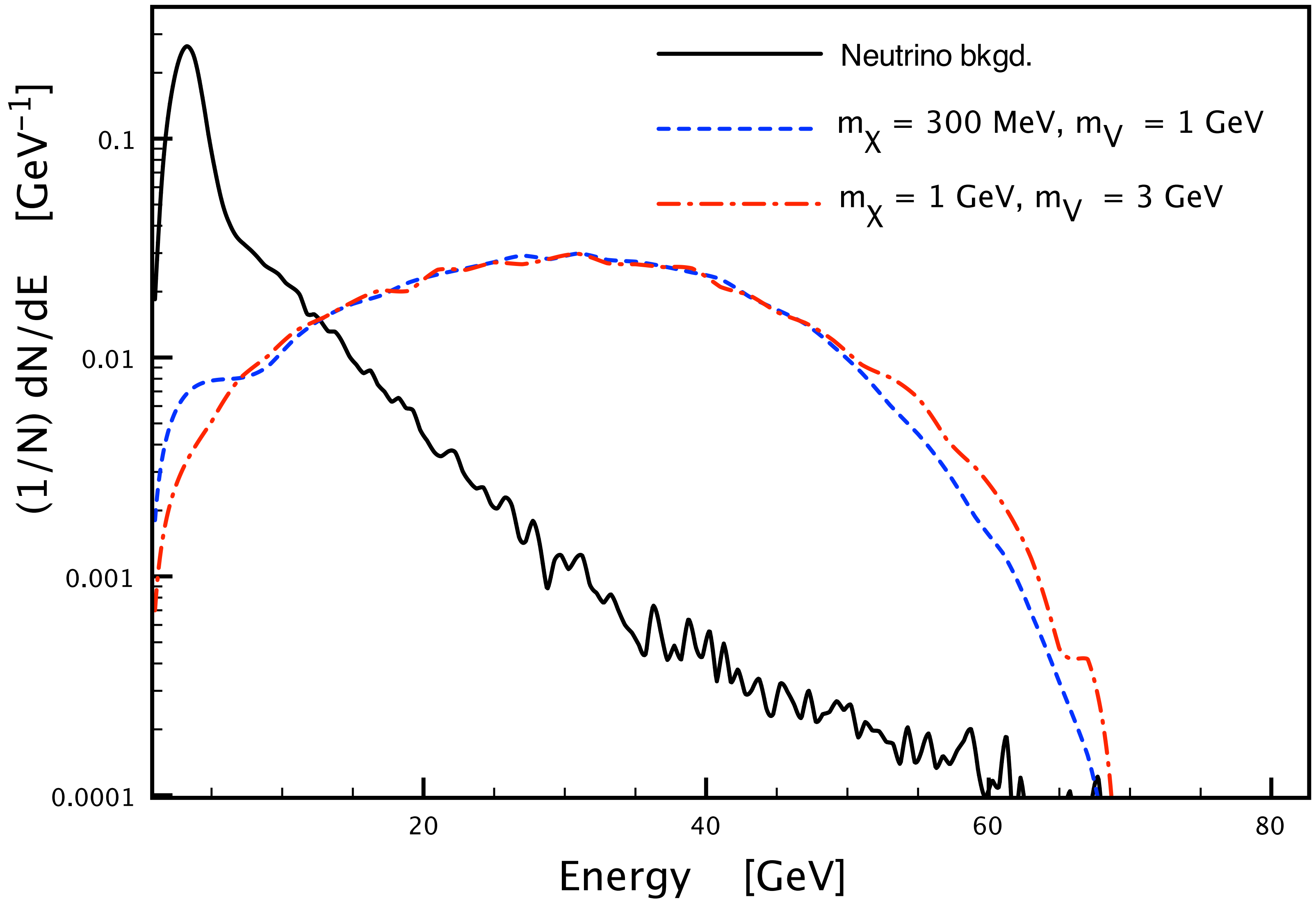
DM Production





Acceptance = 0.042 %

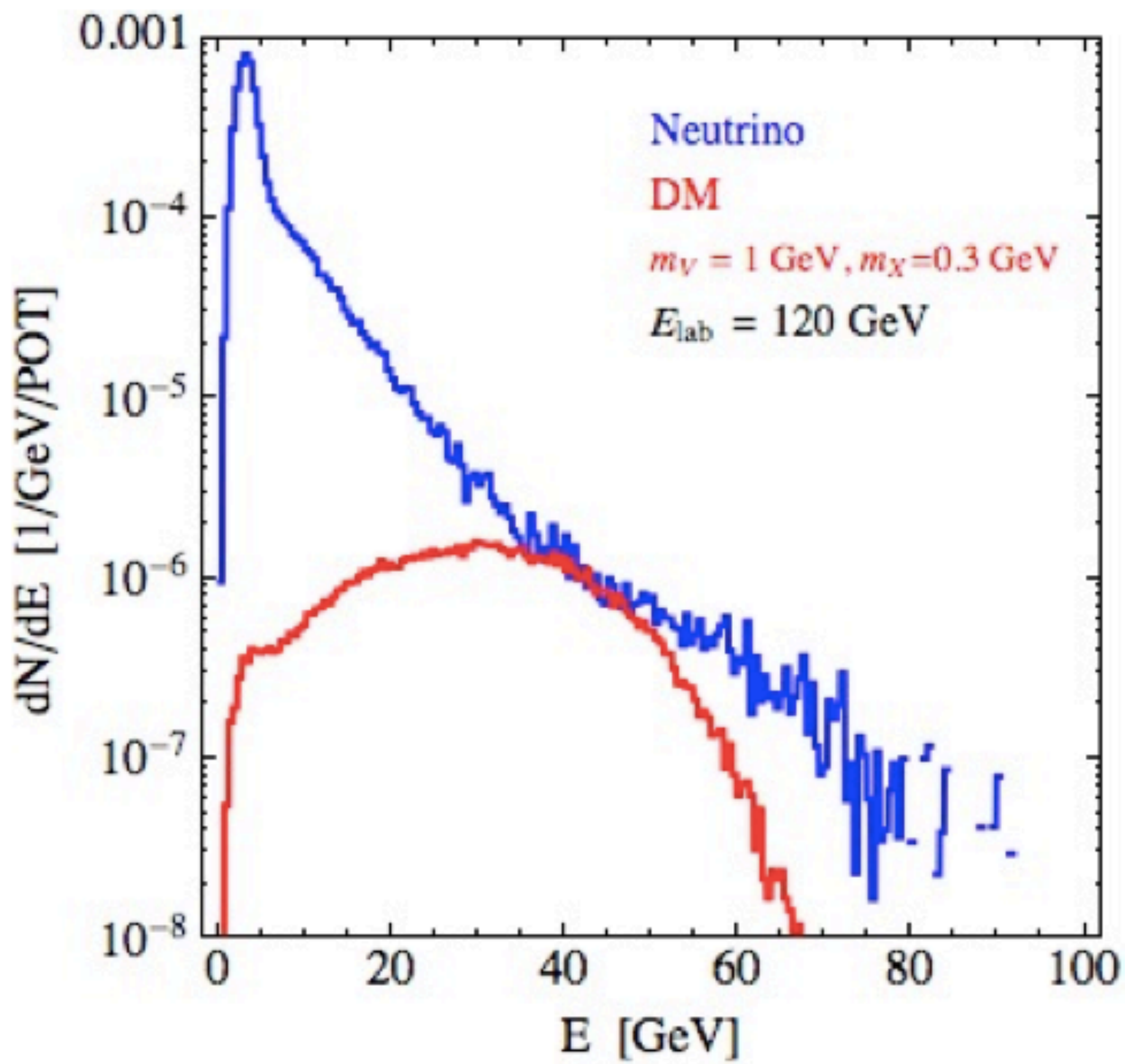
Energy Distribution of DM/neutrinos That Hit Detector



- Neutrinos that hit the detector are much softer
- DM that is produced in the extreme forward direction “carries” the beam energy and is peaked at much higher energies

Energy Distribution of DM/neutrinos That Hit Detector (correctly scaled)

- Naively, situation looks good.
- Neutrino and DM events clearly occupy different regions
- Cut on energy should separate signal & background
- However, our choice of couplings for this test point are “overly-optimistic”
- Taking into account the aforementioned constraints on this model will suppress the signal by at least a factor of ~100
- Clearly, need a way to get rid of those pesky neutrinos



What will the detector see (in electrons)?

- To correctly model the scattering of DM (or neutrinos) and electrons, we need a full-scale Monte Carlo event generator… unfortunately, we're not quite there yet.

- However, in the meantime, we can work with the DM energy distributions from our Madgraph runs by turning them into probability distribution functions (PDFs):

- We do this by first interpolating and normalizing the DM energy distributions:

$$\frac{1}{N_X}\frac{dN_X}{dE_X}$$ (where X = DM or v)

and, then, convoluting with the differential DM-electron (or v-electron) scattering cross section:

$$\frac{d\sigma}{dE_e} = \int_{E_X^{min}(E_e)}^{E_X^{max}} \frac{1}{N_X}\frac{dN_X}{dE_X}\frac{d\sigma_{Xe}}{dE_e}$$

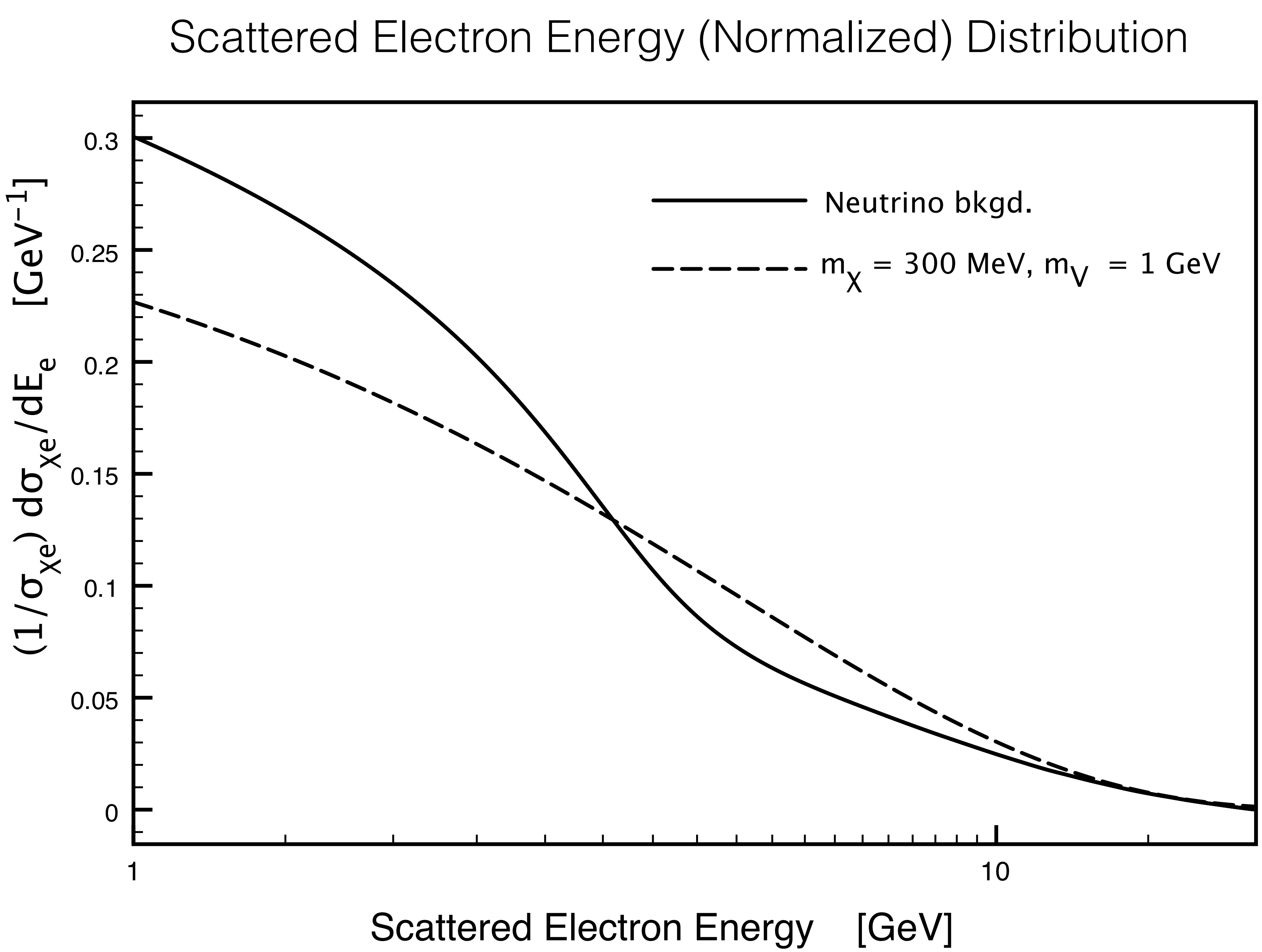
where:

$$\frac{d\sigma_{\chi e}}{dE_e} = 4\pi\epsilon^2\alpha\alpha_D \frac{2m_eE_\chi^2 - \left(2m_eE_\chi - m_eE_e + m_\chi^2 + 2m_e^2\right)(E_e - m_e)}{\left(E_\chi^2 - m_\chi^2\right)\left(m_V^2 + 2m_eE_e - 2m_e^2\right)^2}$$

The χ-e c.s. could be larger than v-e c.s. (~ G_F) for certain parameter choices.

What will the detector see (in electrons)?

- Clearly, the energies of scattered electrons from DM and neutrinos are very similar
- Scattered electrons from DM are slightly harder
- Placing a cut at E > 4 GeV might give a (slight) handle.



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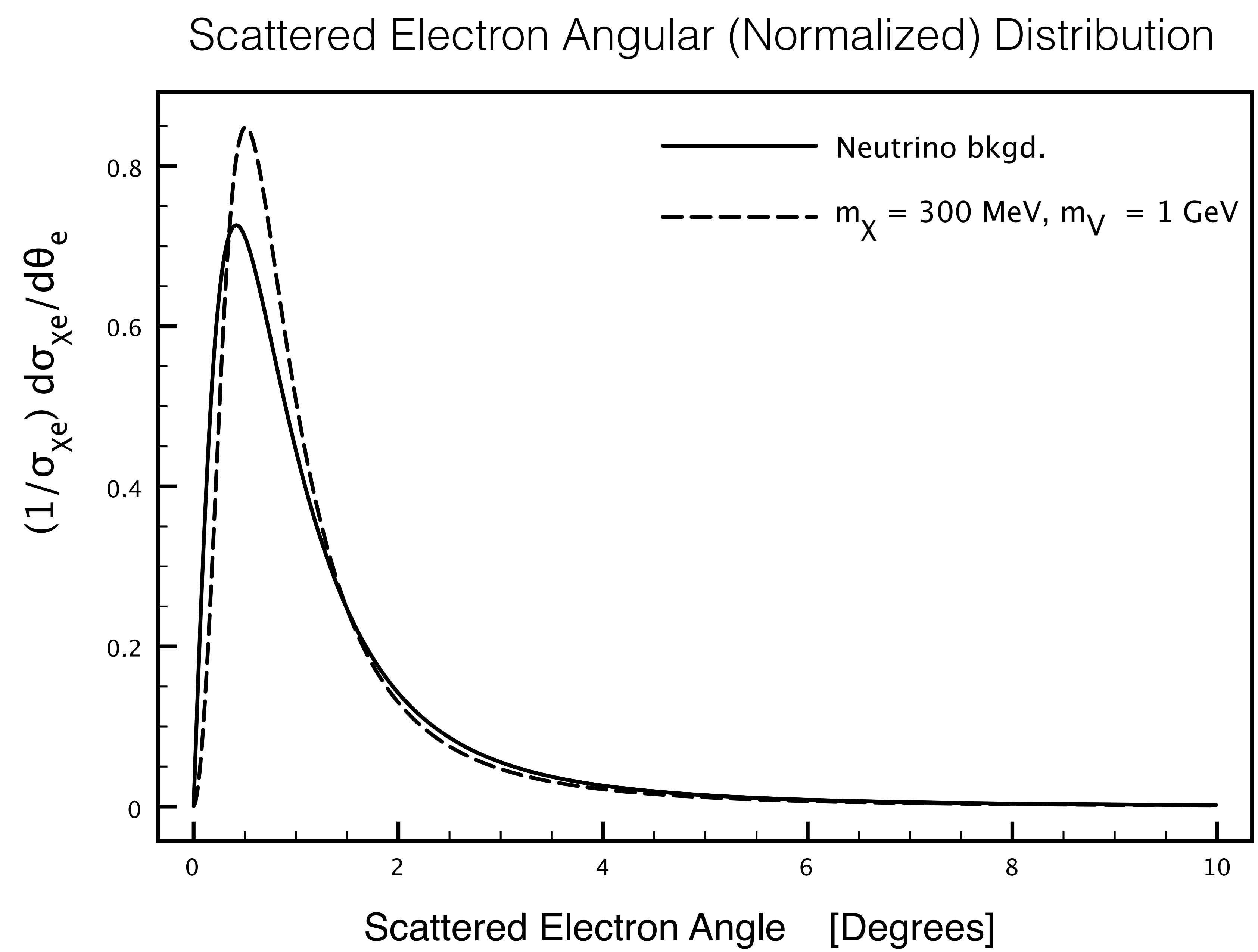
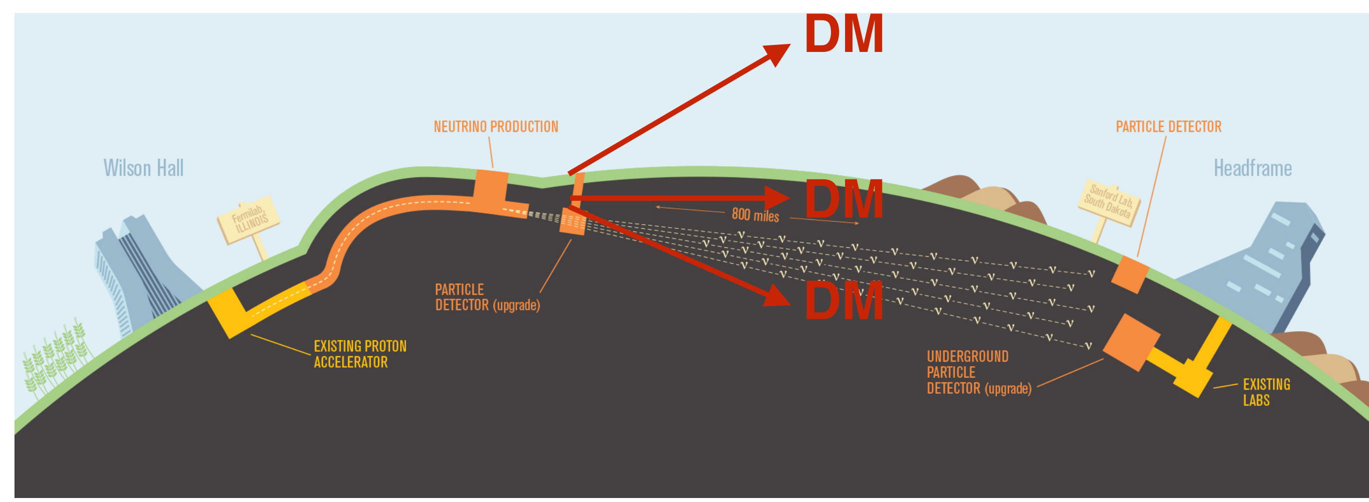


- Unfortunately, the angular distributions of the scattered electrons also appear to be nearly identical :(

~~Conclusions~~ & Outlook

- LBNE offers a potentially exciting option for detecting and studying sub-GeV dark matter.



- We are in the (very) early stages of studying these possibilities.

- Estimated signal rates look very promising! Detection through electron scatterings may be tough, but nuclei scatterings should lead to larger cross sections and scattering rates.

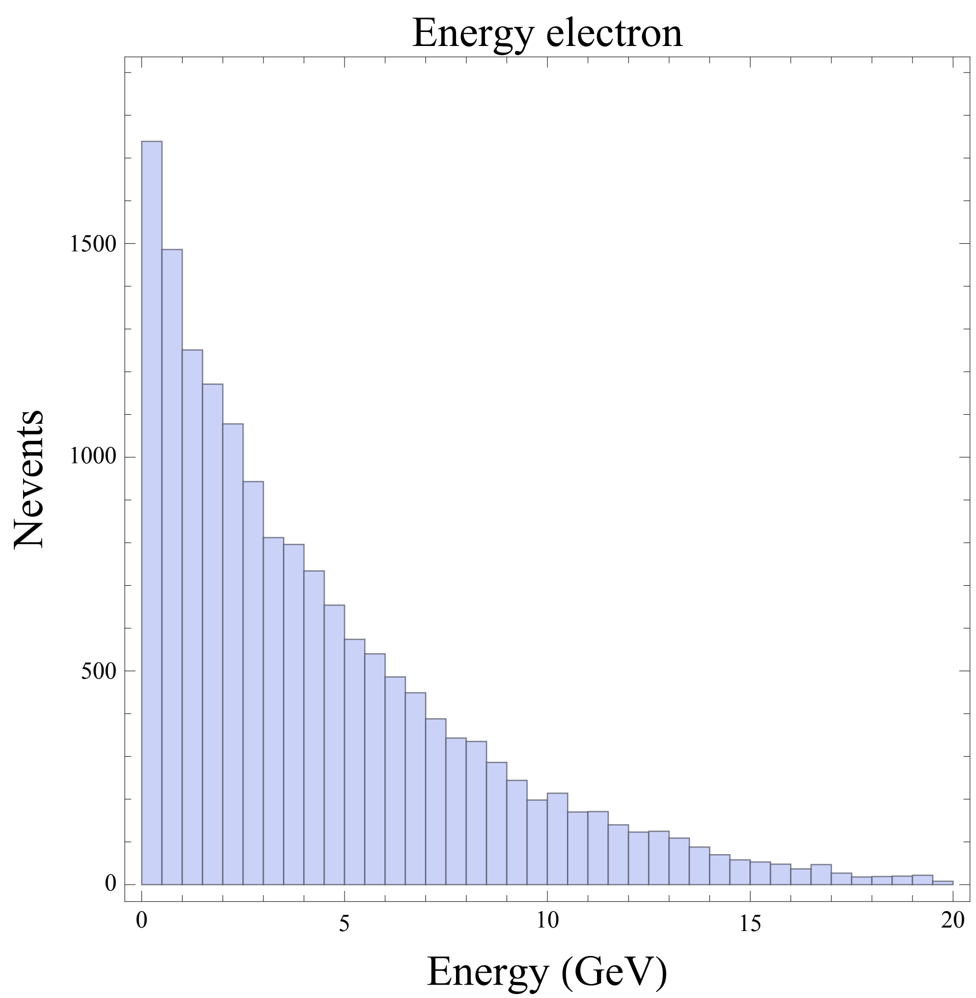
- In any case, neutrino suppression will be imperative. Running in a "beam dump" mode (which can suppress backgrounds by factors of 100 - 1000) would be a nice option. Incorporate this into the design of the beamline(?).

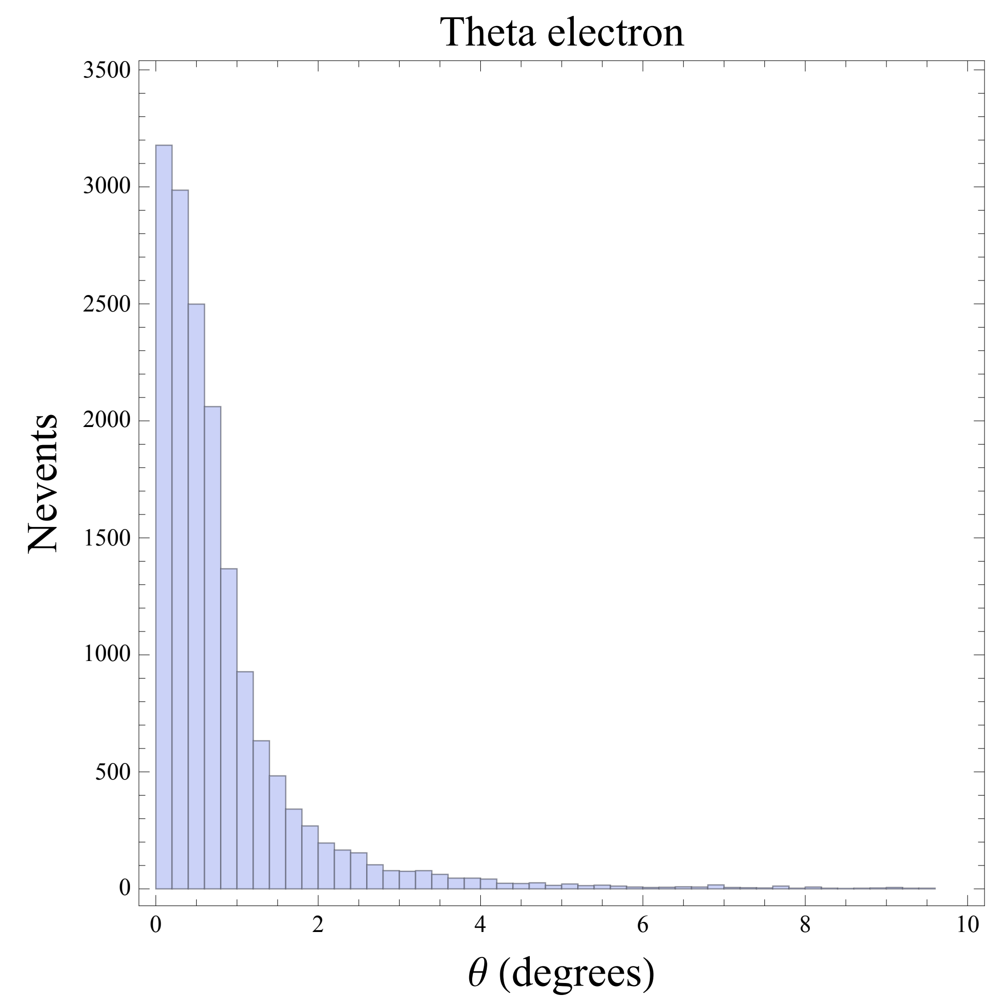
- Another result of our study could be an "optimal" location and size of detector for DM studies… closer and larger detector will result in larger signals.

- Detailed study will require a fully-operational MC event generator…

~~Conclusions~~ & Outlook

We're getting close…





Stay tuned…

Search for DM in LBNE

Thursday, May 1, 2014

New Perspectives on Dark Matter

Jae Yu

University of Texas at Arlington

(for the LBNE DM team)

Search for DM in LBNE

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- Introduction & Scientific Motivation

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- Current Status

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- Current Status
- Summary and conclusions

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Jae Yu
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- Introduction & Scientific Motivation
- LBNE Design
- LBNE Near Neutrino Detector
- Current Status
- Summary and conclusions
- Some thoughts on DM searches in ν experiments

Introduction

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  - known neutrino mass and mixing angle values allow quantum interferometry on a continental scale sensitive to minute effects

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- Neutrino (Flavor) Oscillation is a quantum interference phenomenon with as yet unknown implications for fundamental
  - known neutrino mass and mixing angle values allow quantum interferometry on a continental scale sensitive to minute effects
- Neutrino mass cannot be understood within the Standard Model – calls for new physics
- Our knowledge of neutrino properties is based on only a handful of direct measurements
- Future precision measurements need to test the 3-generation picture and models of neutrino mass

Scientific Motivation

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- CP Violation in neutrino sector?
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Scientific Motivation

- CP Violation in neutrino sector?
  - Violation of a fundamental symmetry; viability of leptogenesis models
- Neutrino Mass Hierarchy
  - GUTs, Dirac vs. Majorana nature and feasibility of $0\nu\beta\beta$ decay
- Testing the Three-Flavor Paradigm
  - Precision measurements of known fundamental mixing parameters
  - New physics → non-standard interactions, sterile neutrinos… (with beam + atmospheric ν sources)
  - Precision neutrino interactions studies (near detector)

Scientific Motivation II

Further details: “Science Opportunities w/ LBNE,” arXiv:1307.7335.

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- Other fundamental physics enabled by massive detector
  - Proton decay measurement
    - Test of GUT

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Scientific Opportunities with the Long-Baseline Neutrino Experiment

July 30, 2013

The LBNE Collaboration

arXiv:1307.7335v1 [hep-ex] 28 Jul 2013

Further details: “Science Opportunities w/ LBNE,” arXiv:1307.7335.

Evolving LBNE Collaboration

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Colorado State
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Drexel
Duke
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Irvine
Kansas State
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Lawrence Berkeley NL
Livermore NL
London UCL
Los Alamos NL
Louisiana State
Maryland
Michigan State
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Fermilab, March 2013

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South Dakota State
SDSMT
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Tufts
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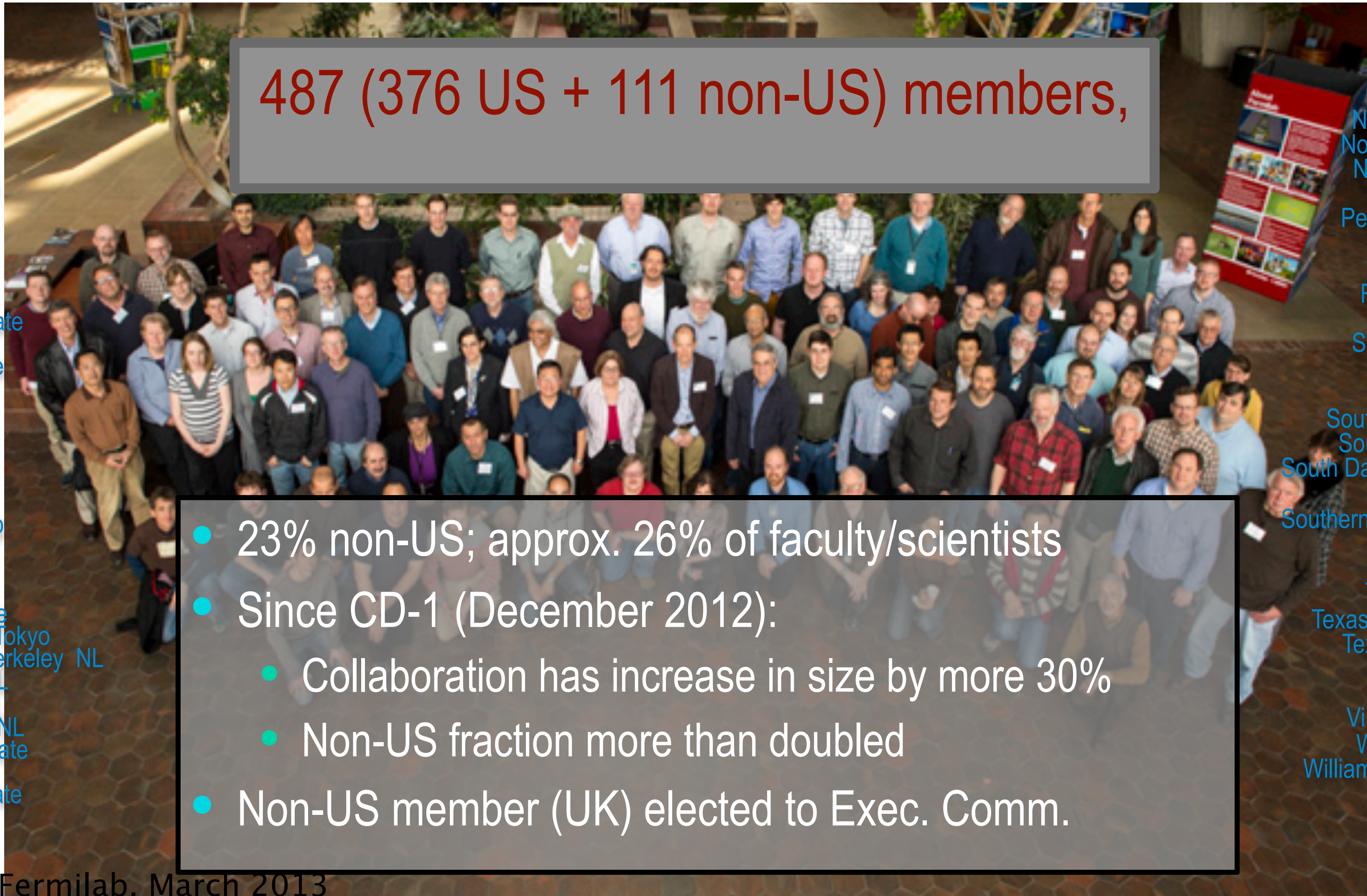

487 (376 US + 111 non-US) members,

- 23% non-US; approx. 26% of faculty/scientists
- Since CD-1 (December 2012):
  - Collaboration has increase in size by more 30%
  - Non-US fraction more than doubled
- Non-US member (UK) elected to Exec. Comm.

Fermilab, March 2013

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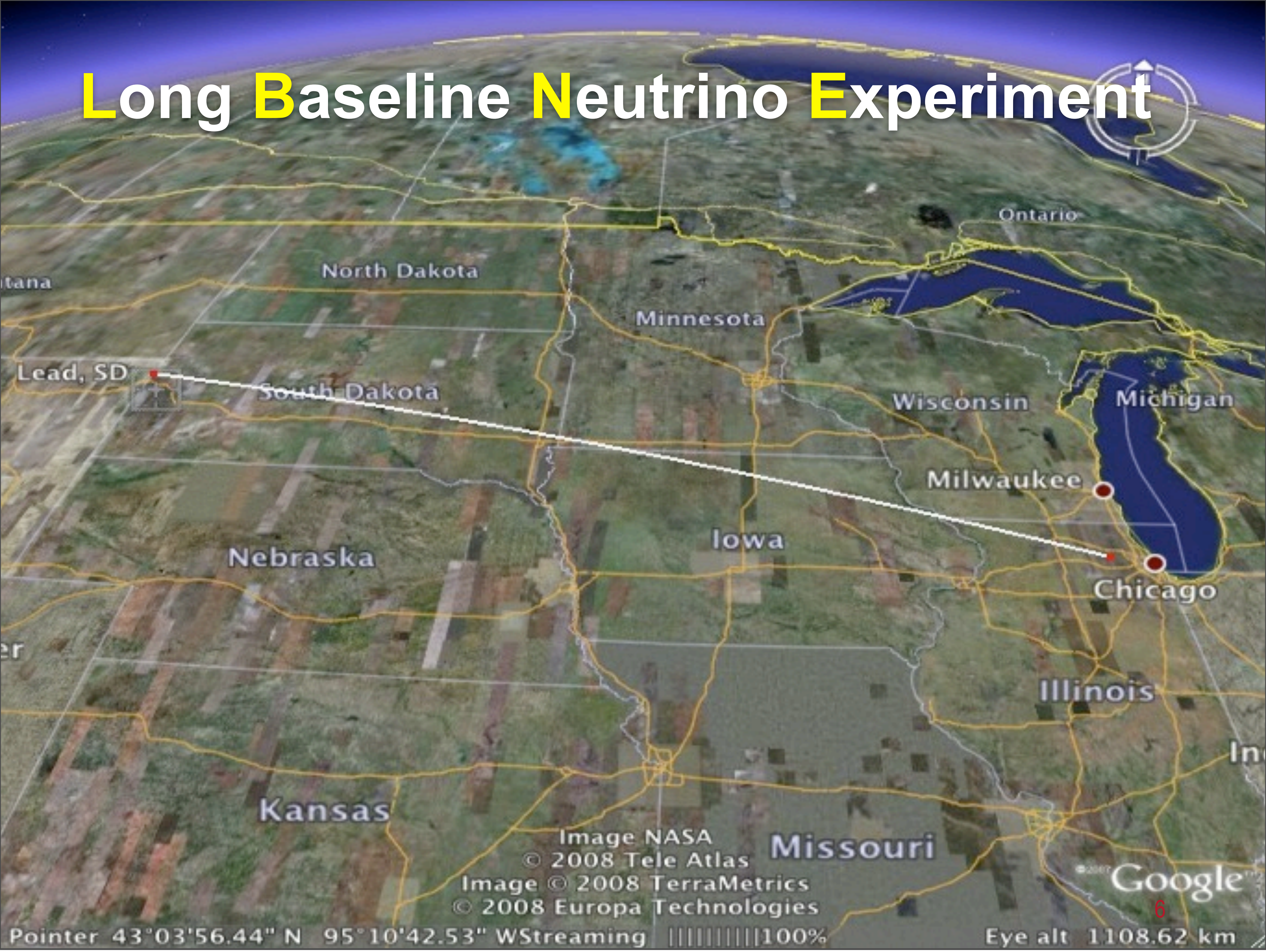
Long Baseline Neutrino Experiment



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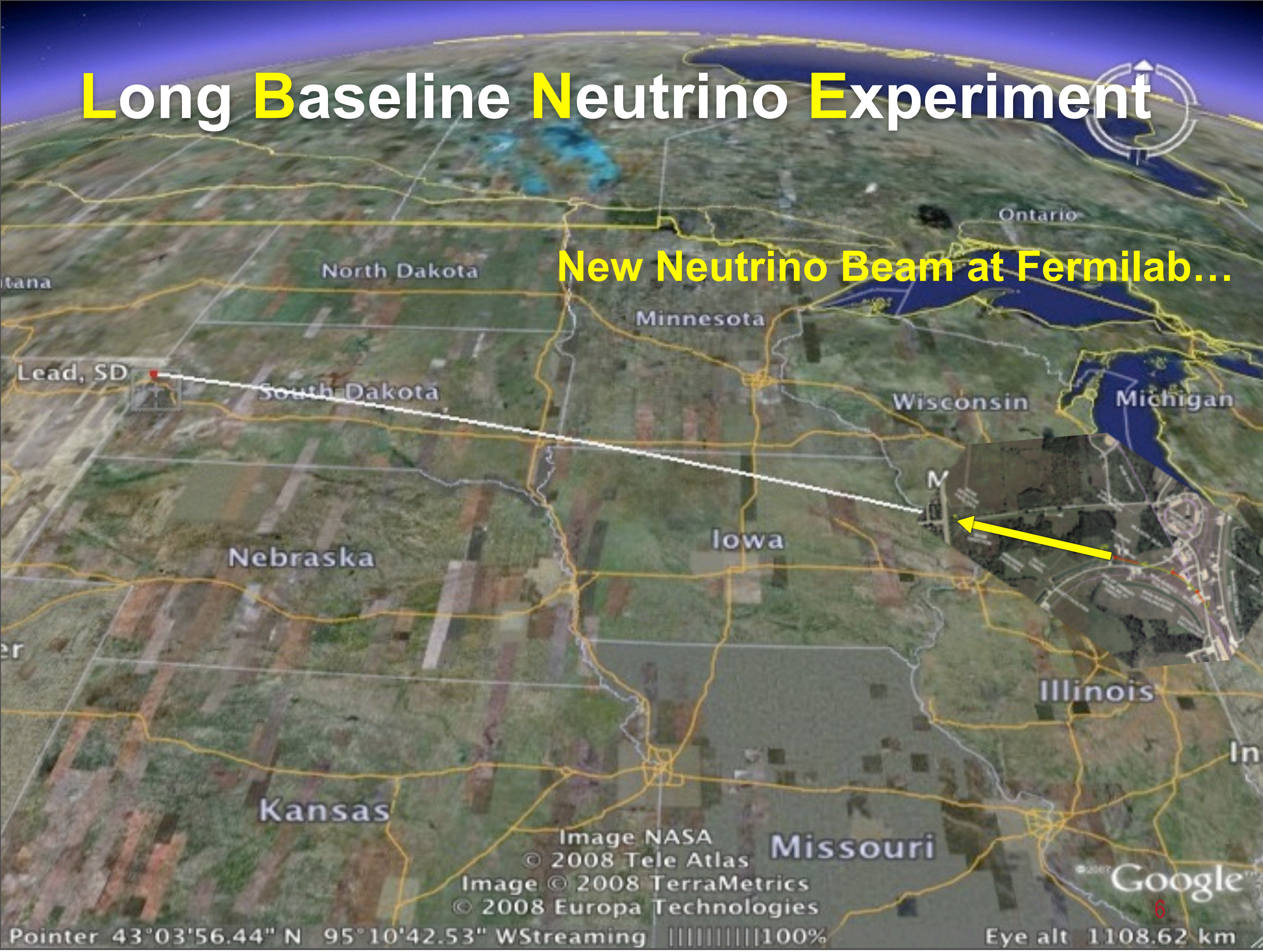
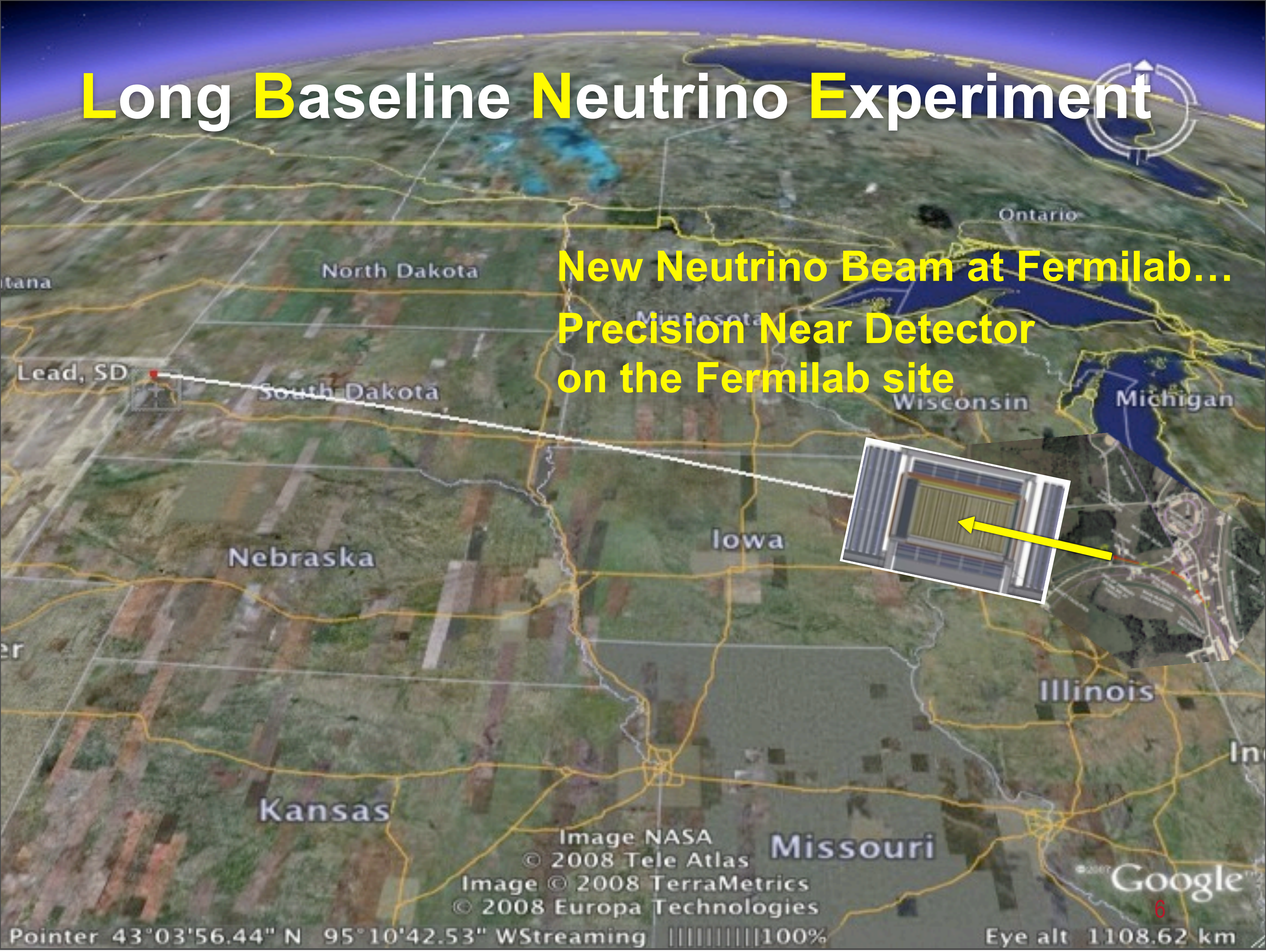


Long Baseline Neutrino Experiment

New Neutrino Beam at Fermilab…

Precision Near Detector on the Fermilab site



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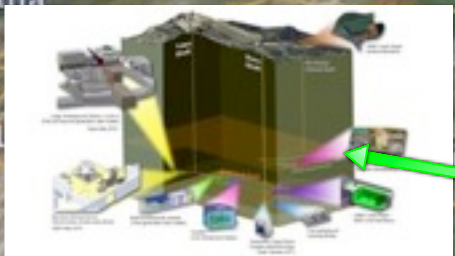


1300 km

…aimed at the Sanford Underground
Research Facility (SURF)
in Lead, South Dakota

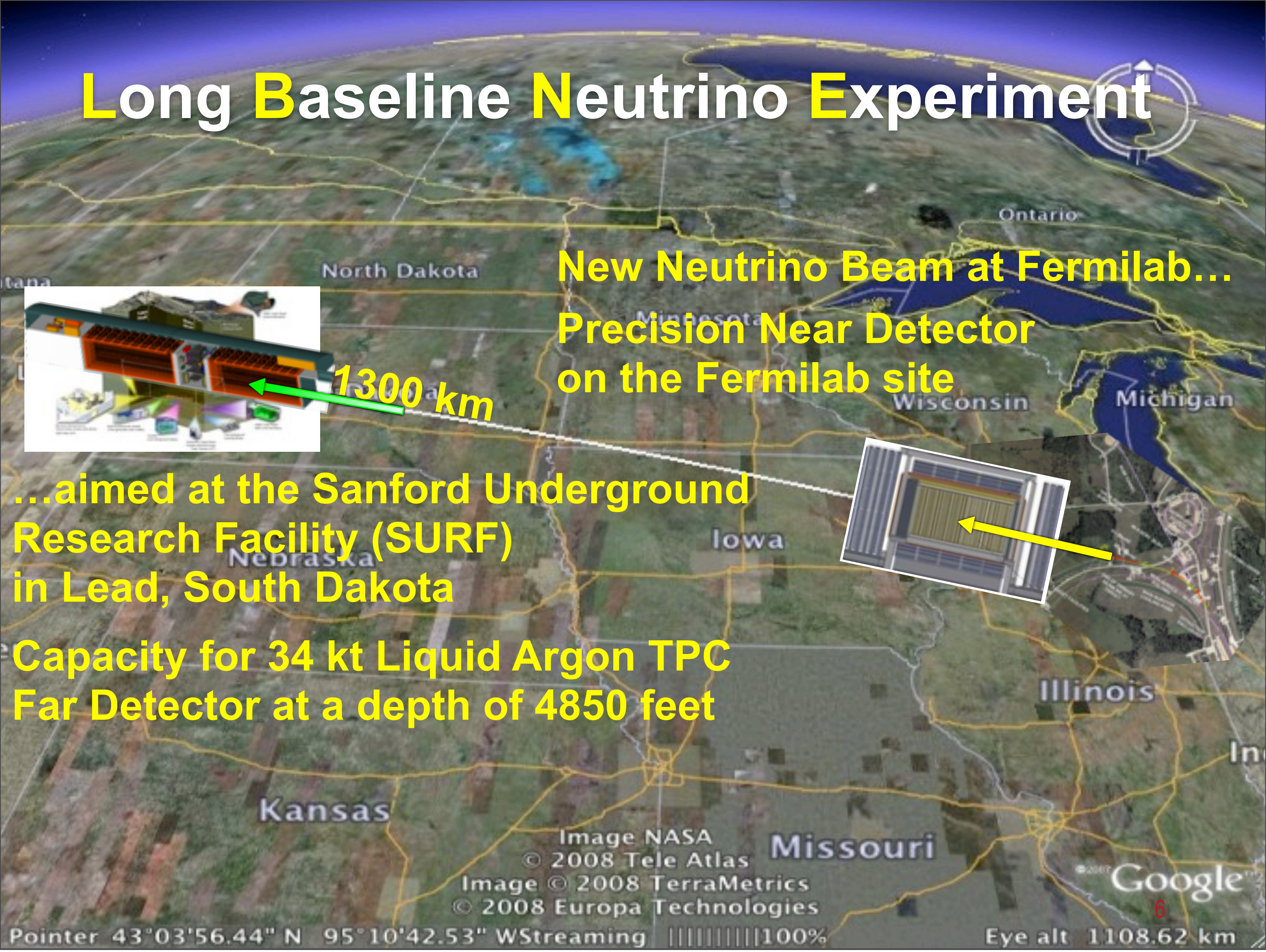
Long Baseline Neutrino Experiment

New Neutrino Beam at Fermilab…

Precision Near Detector
on the Fermilab site

…aimed at the Sanford Underground
Research Facility (SURF)
in Lead, South Dakota

Capacity for 34 kt Liquid Argon TPC
Far Detector at a depth of 4850 feet



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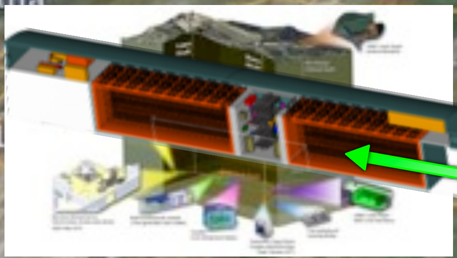

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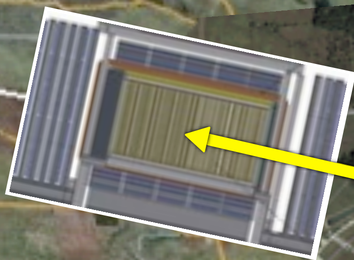


…aimed at the Sanford Underground Research Facility (SURF) in Lead, South Dakota

Capacity for 34 kt Liquid Argon TPC Far Detector at a depth of 4850 feet

And all the Conventional Facilities required to support the beam and detectors

Evolving Scope of the LBNE Project

Evolving Scope of the LBNE Project

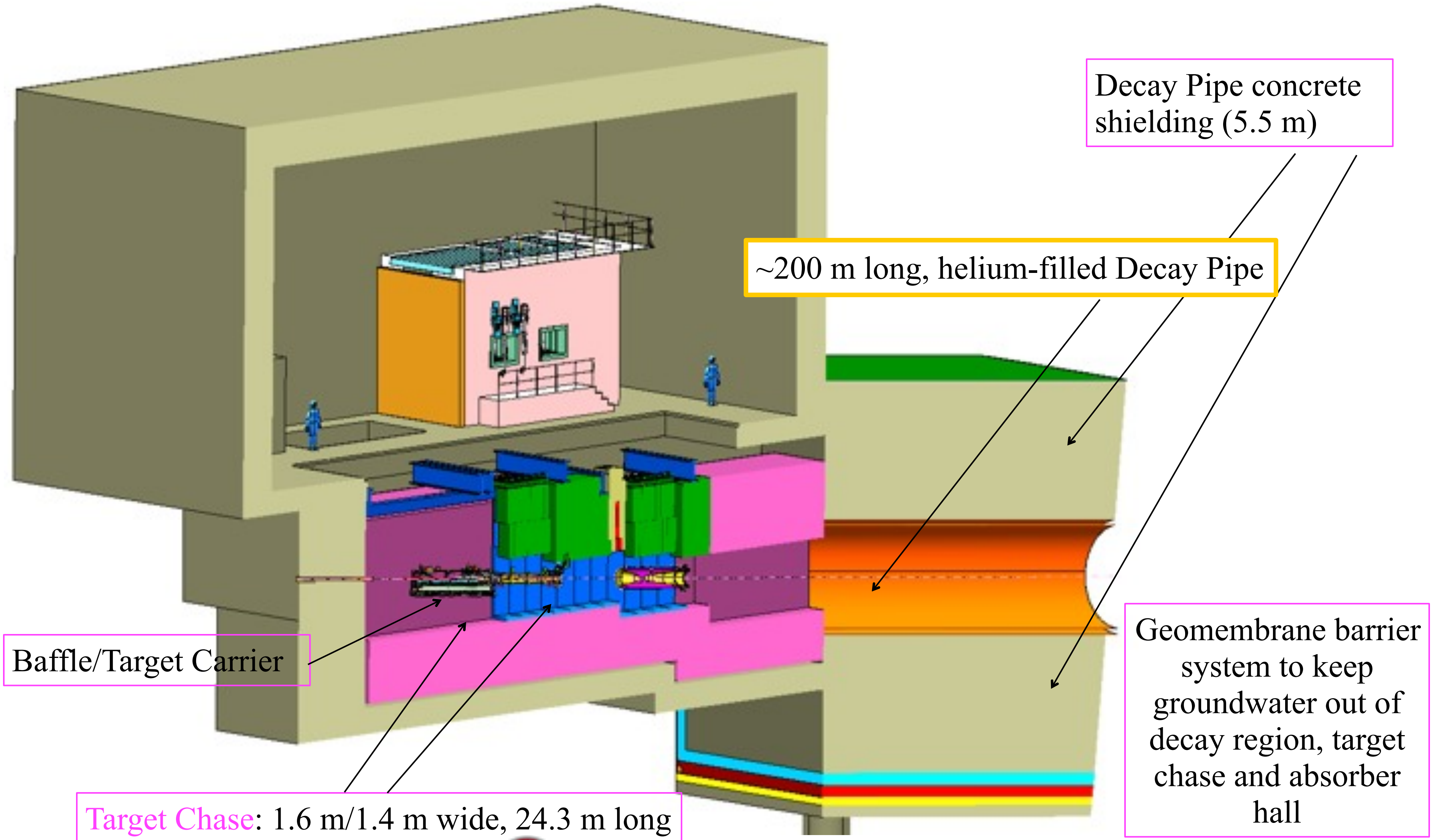
- We are developing international partnerships, with the goal of delivering an initial project consisting of:
  - A neutrino beamline, operating initially at 1.2 MW
  - A highly-capable near detector system,
  - A ≥10 kt fiducial mass far detector underground (4850ft) at SURF
  - CF including a cavern for a full 34 kt fiducial mass LArTPC system.
  - The designs of the near and far detectors (and perhaps the beam) will incorporate concepts from new partners.
- DOE/HEP supports this approach
- The planned project allows for future upgrades:
  - The beamline is designed to upgradeable to ≥2.3 MW proton beam power
  - Future detector module(s) can be installed in the underground cavern.

LBNE Beamline Design

Designed for 1.2 MW initial beam power; upgradeable to at least 2.3 MW.

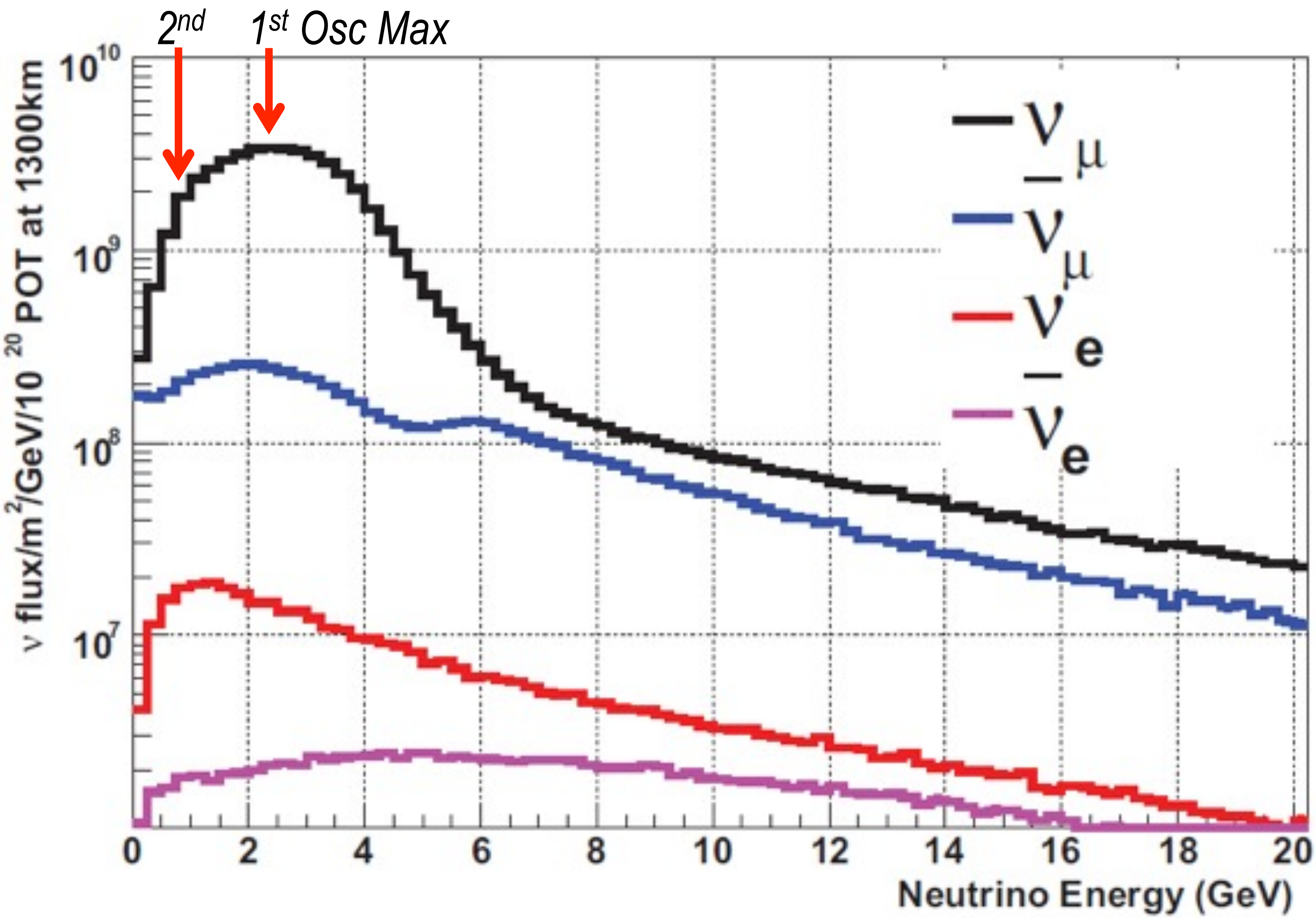
Ready for beam in 2022/2023 (depending on funding)

Target Hall/Decay Pipe Layout



Neutrino Flux Spectrum

at Far Detector in the Absence of Oscillations



Beam Improvements Under Consideration

Beam Improvements Under Consideration

Changes	0.5-2 GeV		2-5 GeV		Extra Cost
Horn current 200 kA $\rightarrow$ 230 kA	1.00		1.12		\$0
Proton beam 120 $\rightarrow$ 80 GeV, 700 kW	1.14		1.05		\$0
Target graphite $\rightarrow$ Be	1.10	31%	1.00	28%	$<$ 1 M\$
DP Air $\rightarrow$ He	1.07		1.11		$\sim$ 8 M\$
DP diameter 4 m $\rightarrow$ 6 m	1.06		1.02		$\sim$ 17 M\$
DP length 200 m $\rightarrow$ 250 m	1.04		1.12		$\sim$ 30 M\$
Total	1.48		1.50		

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Proton beam 120 $\rightarrow$ 80 GeV, 700 kW	1.14	31%	1.05	28%	\$0
Target graphite $\rightarrow$ Be	1.10		1.00		$<$ 1 M\$
DP Air $\rightarrow$ He *Recently approved*	1.07		1.11		$\sim$ 8 M\$
DP diameter 4 m $\rightarrow$ 6 m	1.06		1.02		$\sim$ 17 M\$
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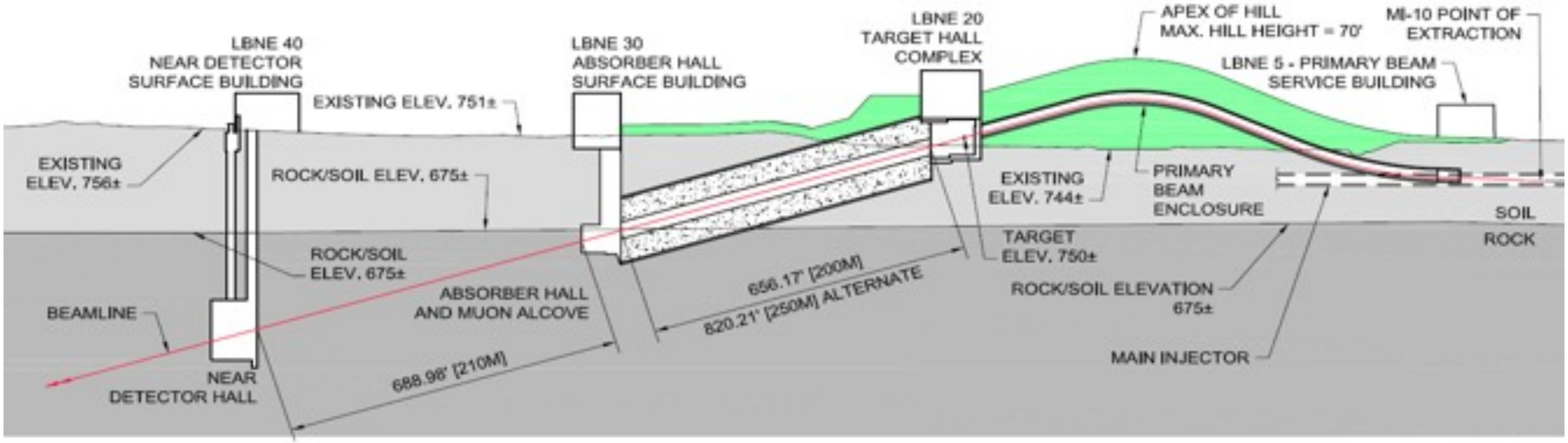

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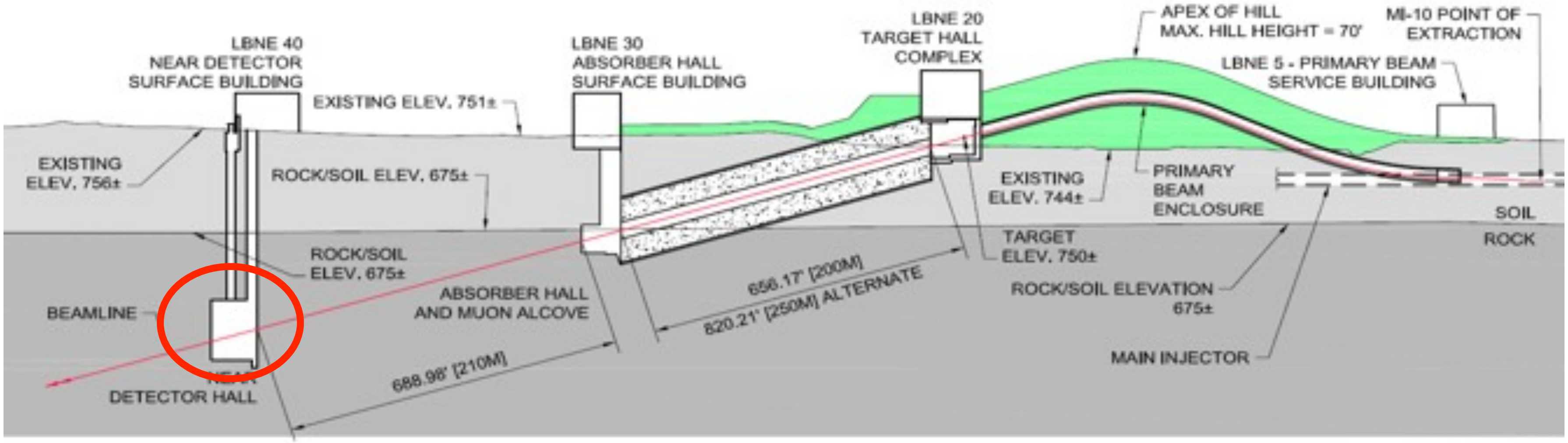
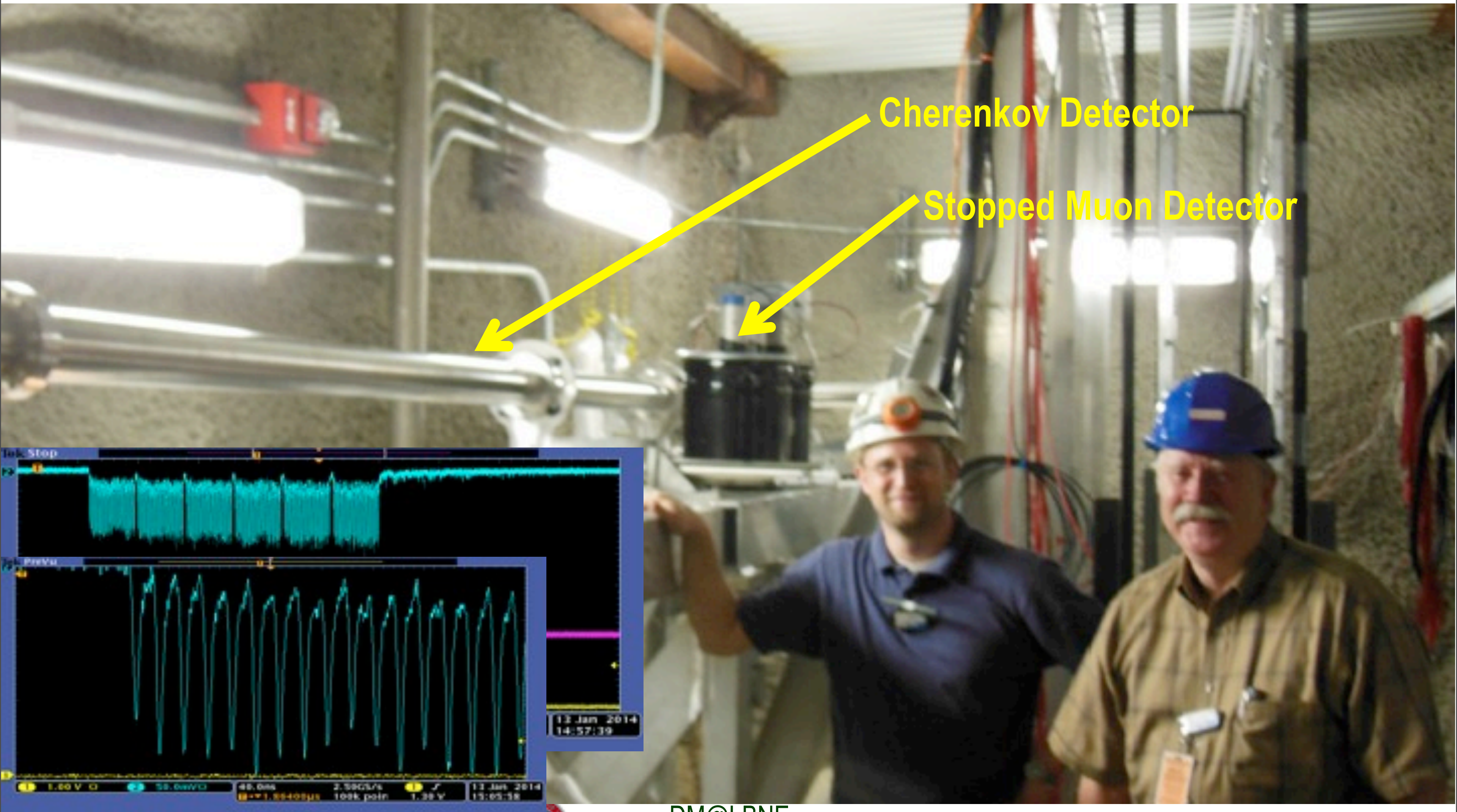
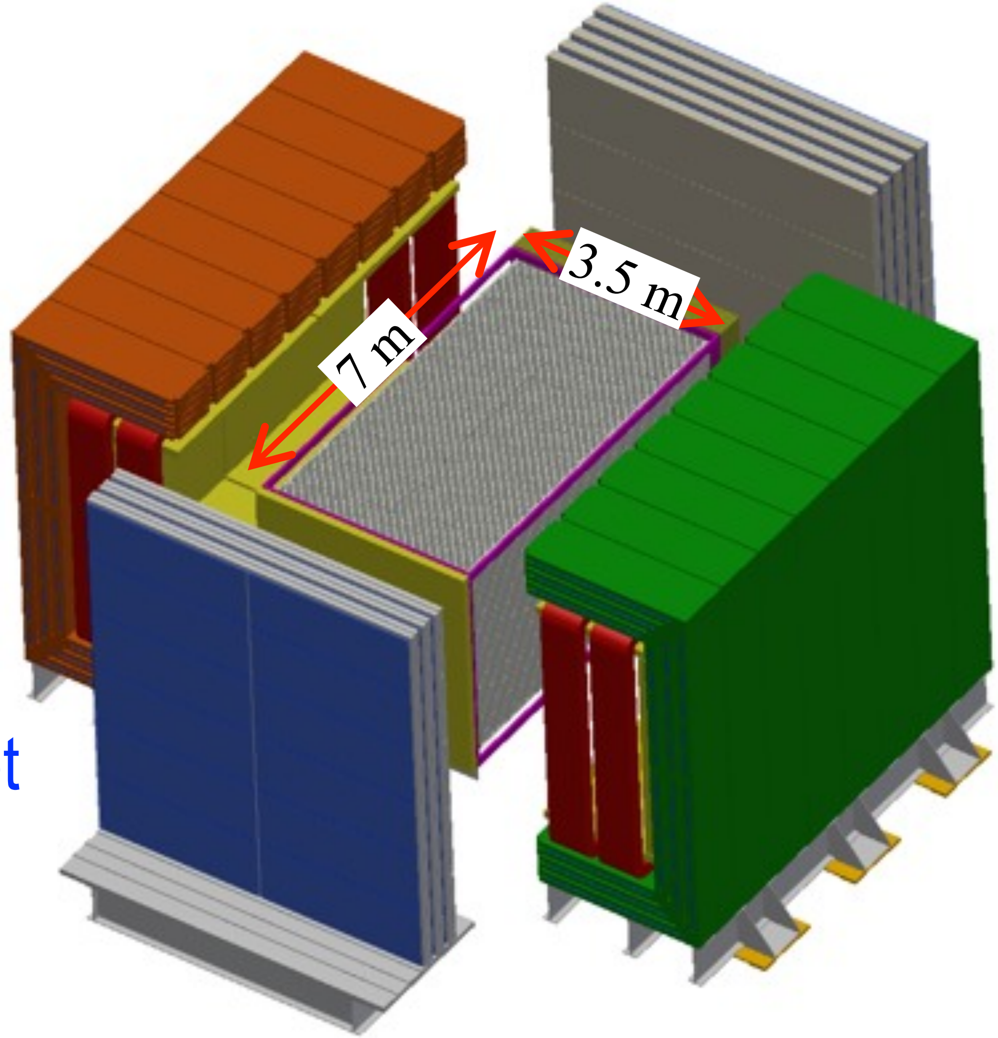


Prototype Muon Detectors in NuMI Beamline

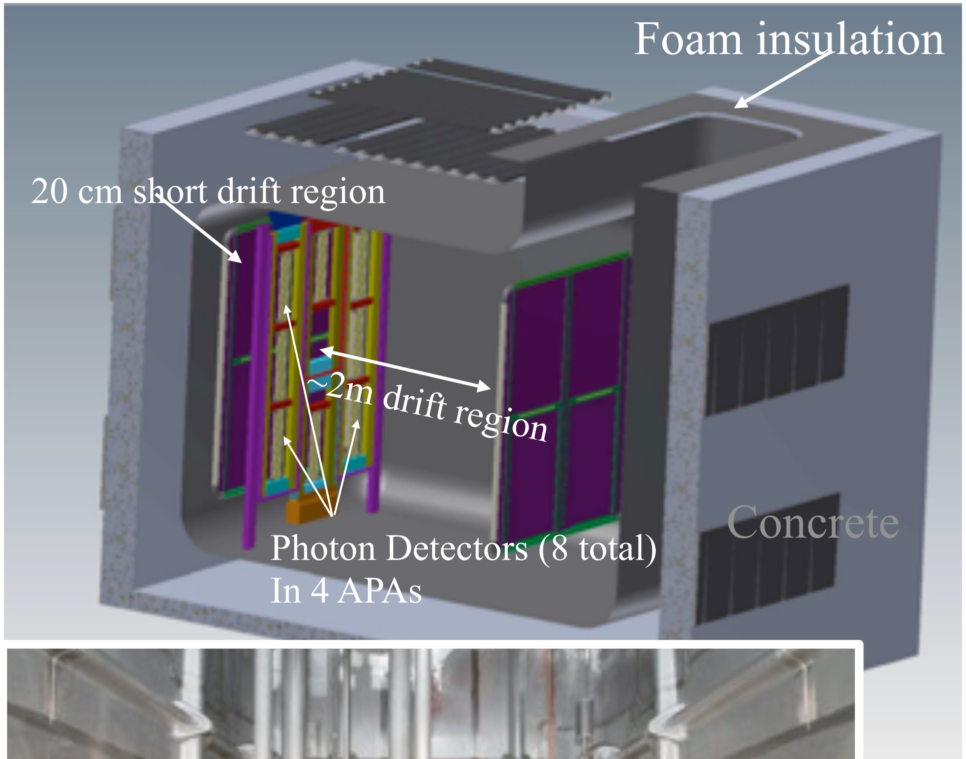


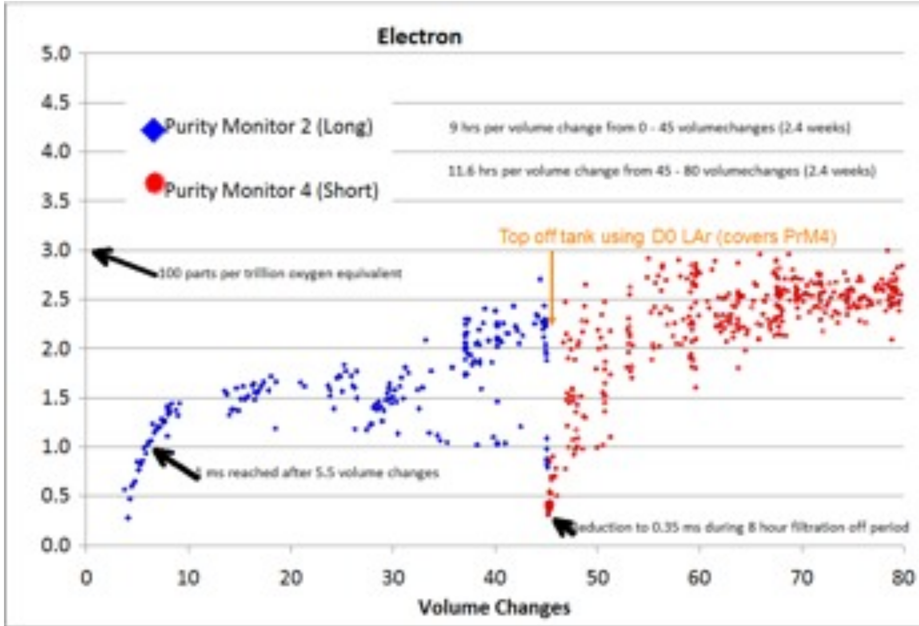
Near Neutrino Detector

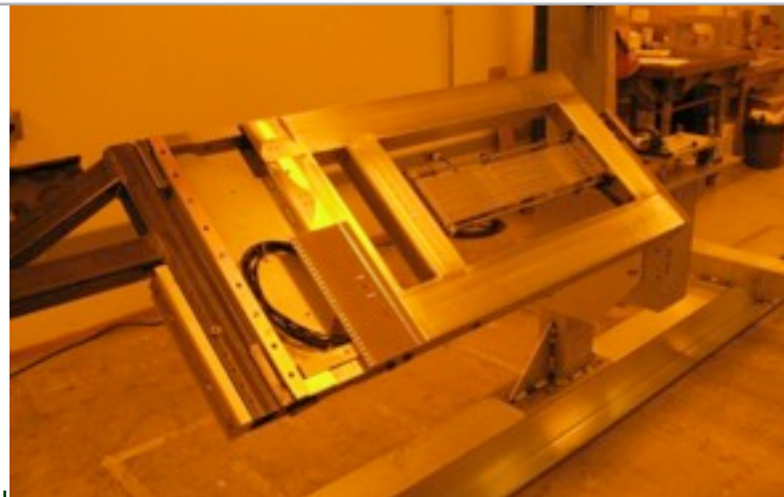
- Proposed by collaborators from the Indian institutions
- High precision straw-tube tracker with embedded high-pressure argon gas targets
- 4π electromagnetic calorimeter and muon identification systems
- Large-aperture dipole magnet



35 t Prototype Cryostat and Prototype TPC Detector

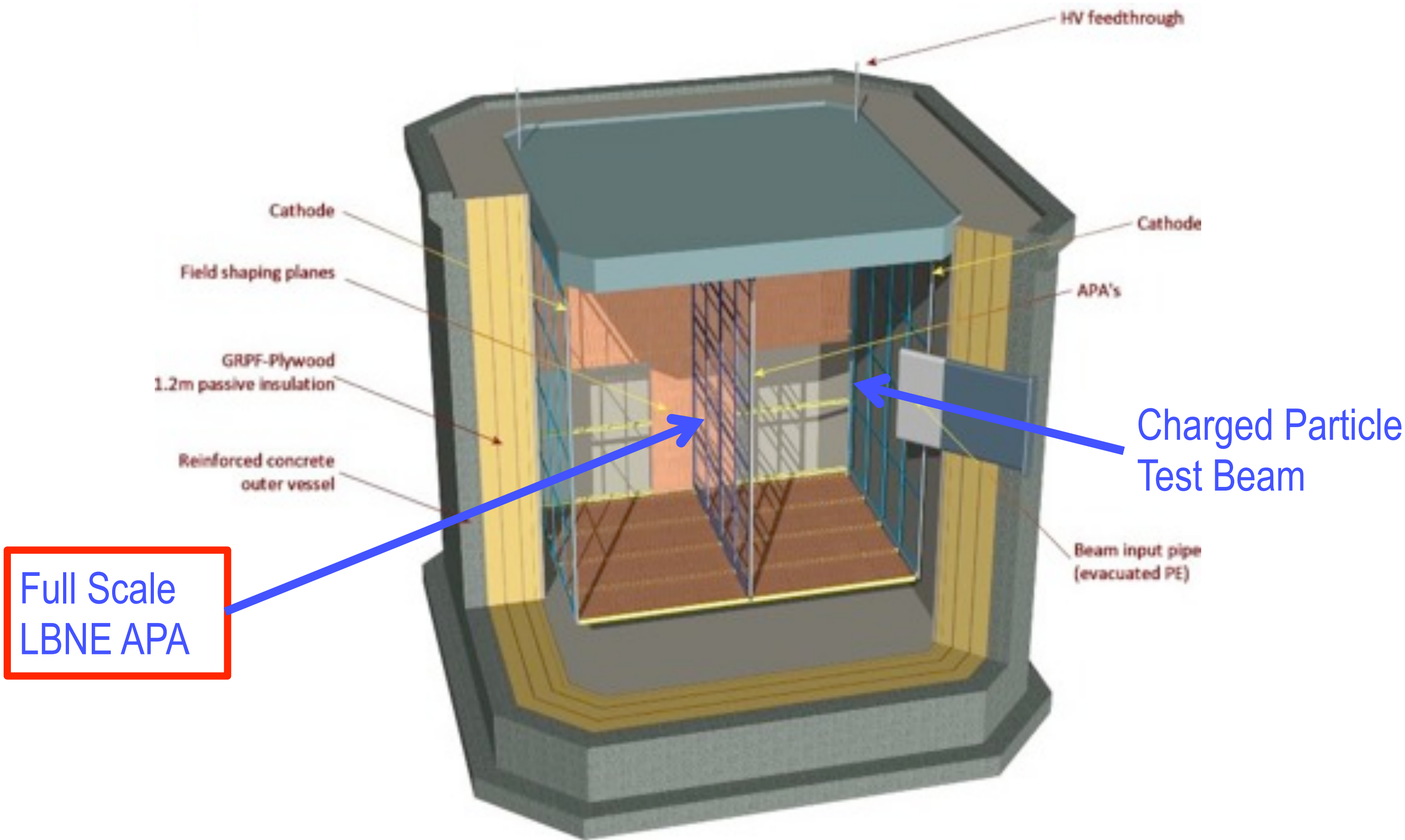






Full-Scale Prototype in LAGUNA-LBNO Cryostat @ CERN

- We are developing a plan to test full-scale LBNE drift cell(s) in the 8x8x8 m^3 cryostat to be built at CERN as part of WA105.



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Beam Energy (GeV)	8	8	120	120	120	120	60 – 120
Beam Power (MW)	0.04	0.04	0.3	0.3	0.7	0.3	1.2
Near Det. Mass (t)	1000 (818fid)	170 (60 fid)		1000	222 (20 fid)	(5.6fid)	8
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- How can DM experiment co-exist with neutrino experiments?
  - How about tilting the beam?

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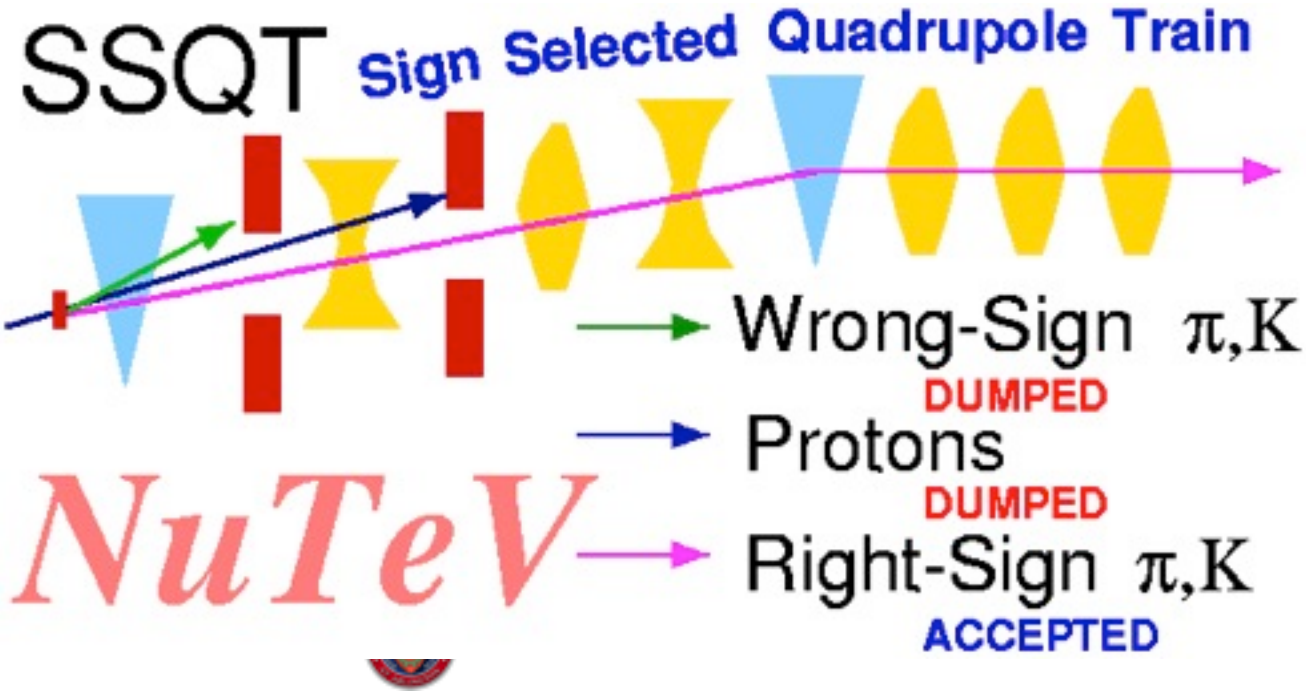

Thursday,

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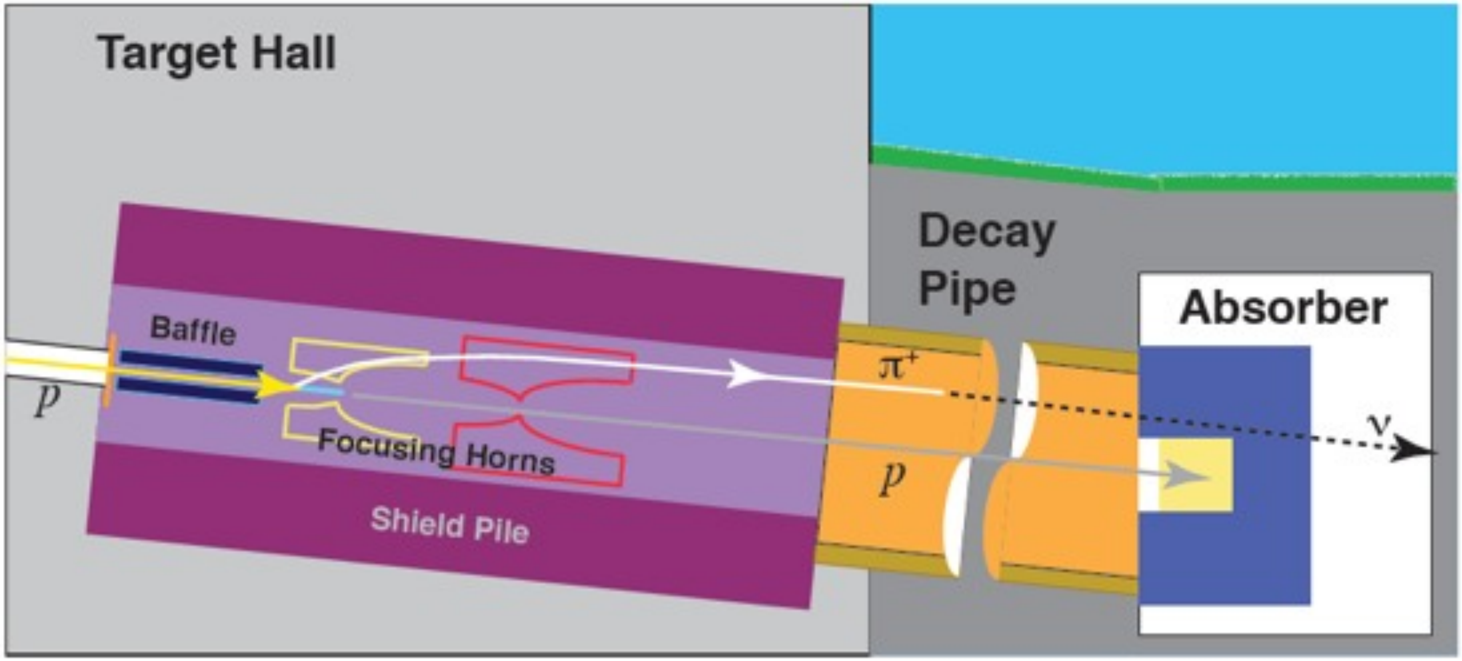

Figure 3–1: A cartoon of the neutrino beamline showing the major components of the neutrino beam. From left to right, the beam window, horn-protection baffle, target, the two toroidal focusing horns, decay pipe and absorber. The air volume surrounding the components between the window and the decay pipe is called the target "chase". The target chase and rooms for ancillary equipment (power supplies, cooling, air recirculation and so on) is included in the area called the target complex (not pictured).

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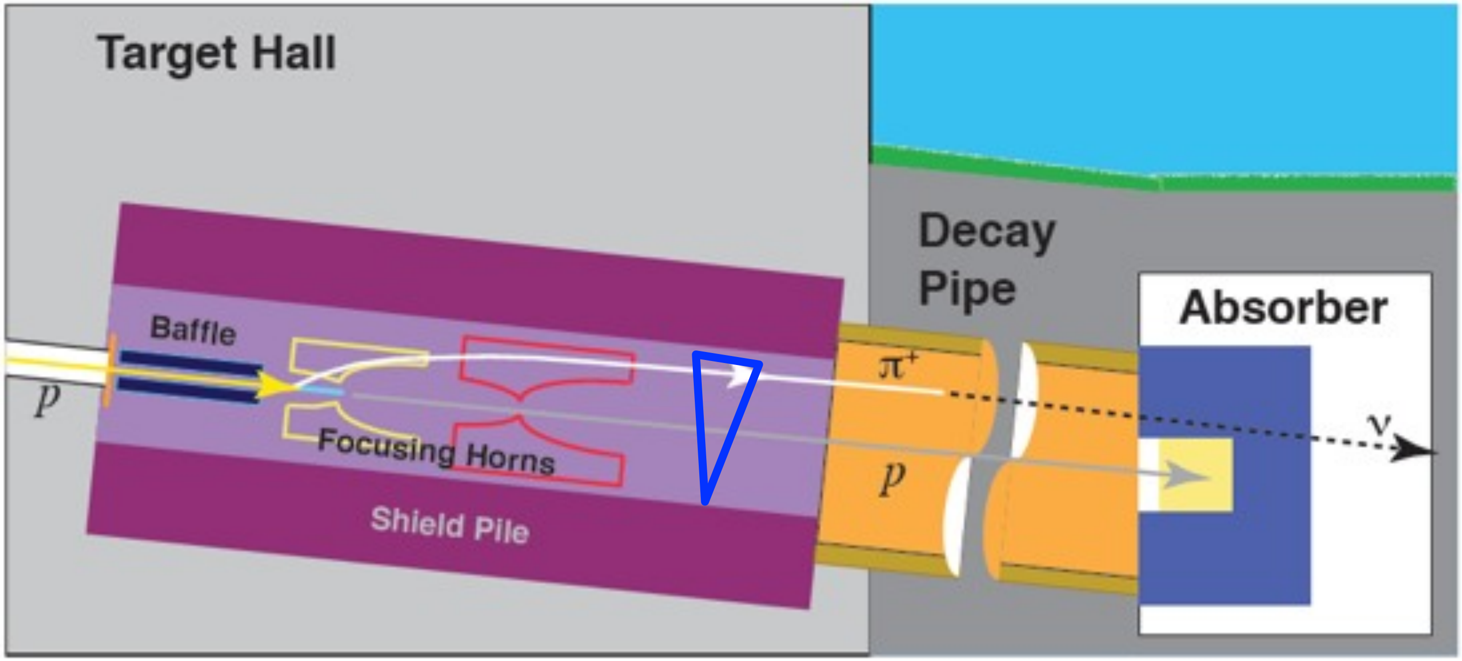

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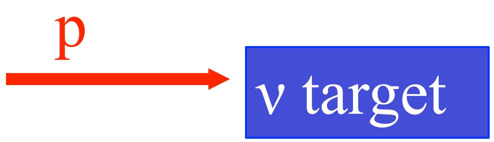

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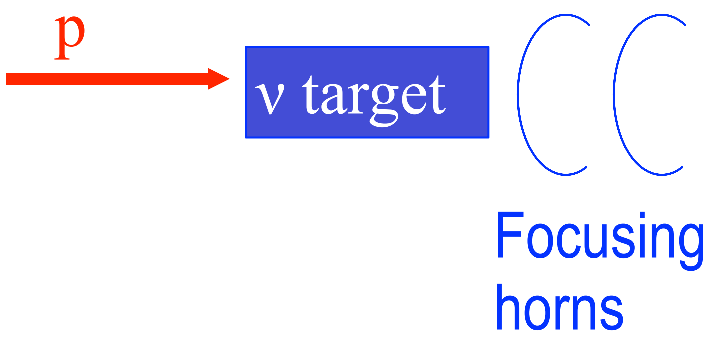

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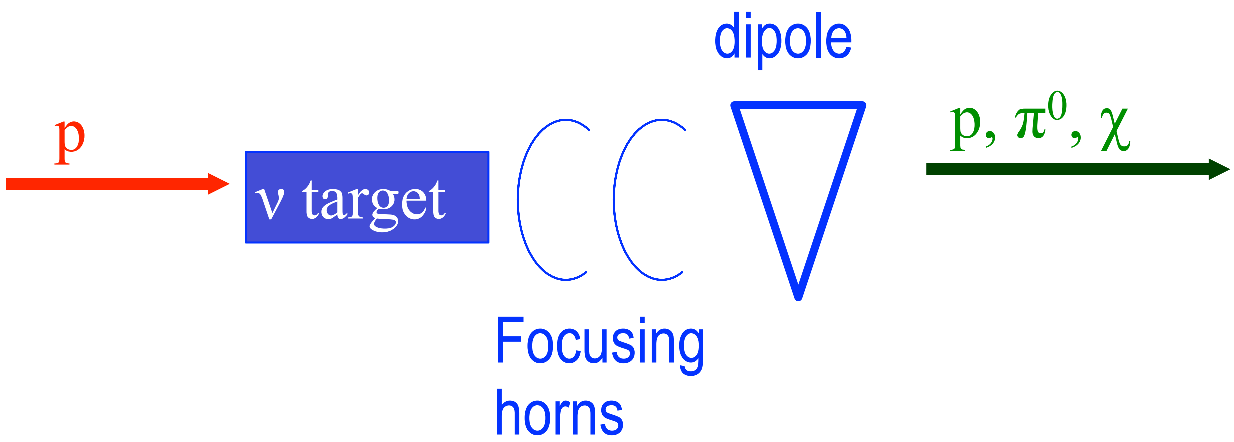

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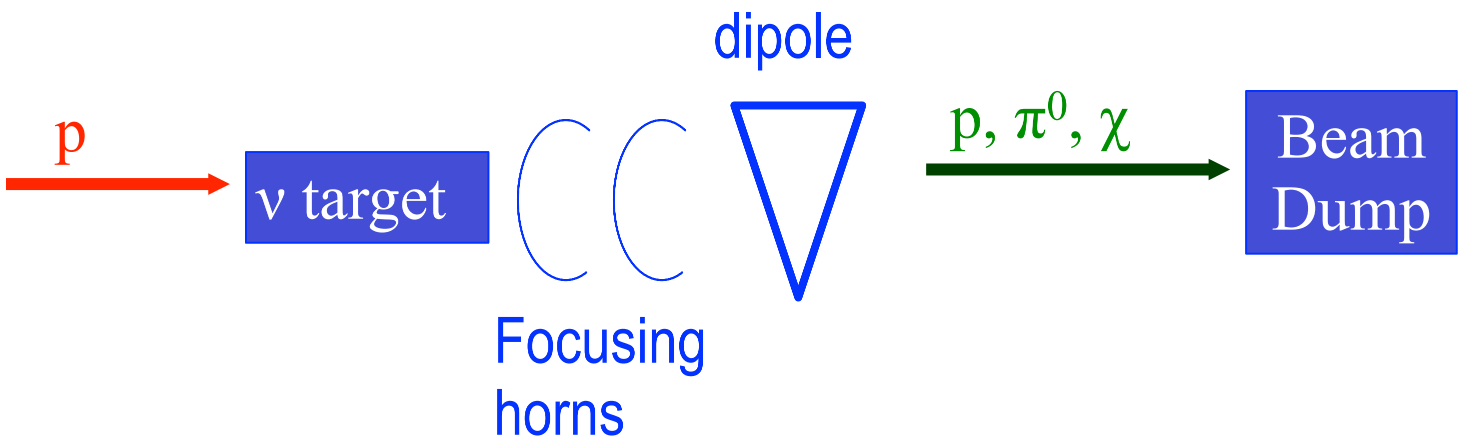

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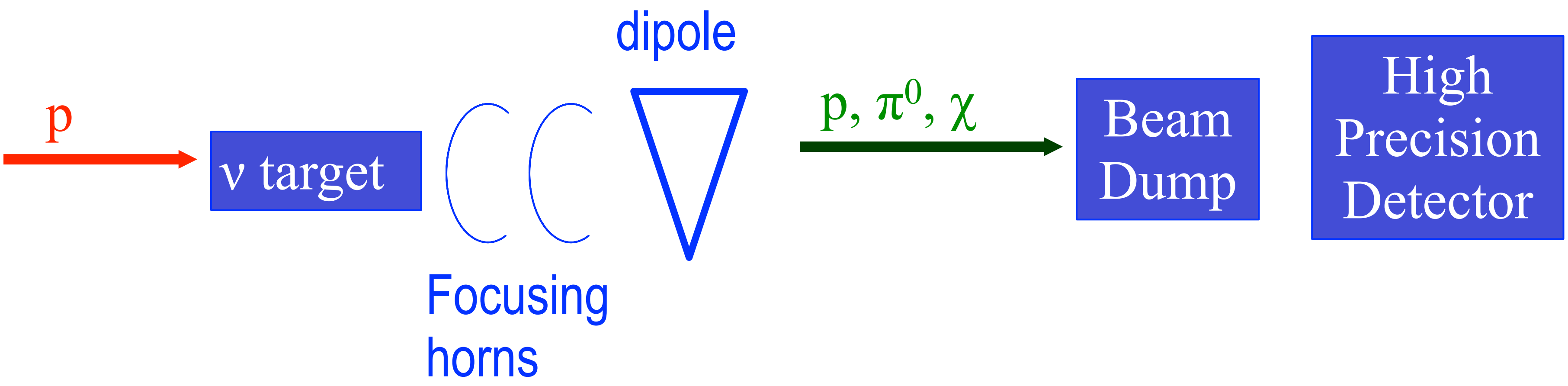

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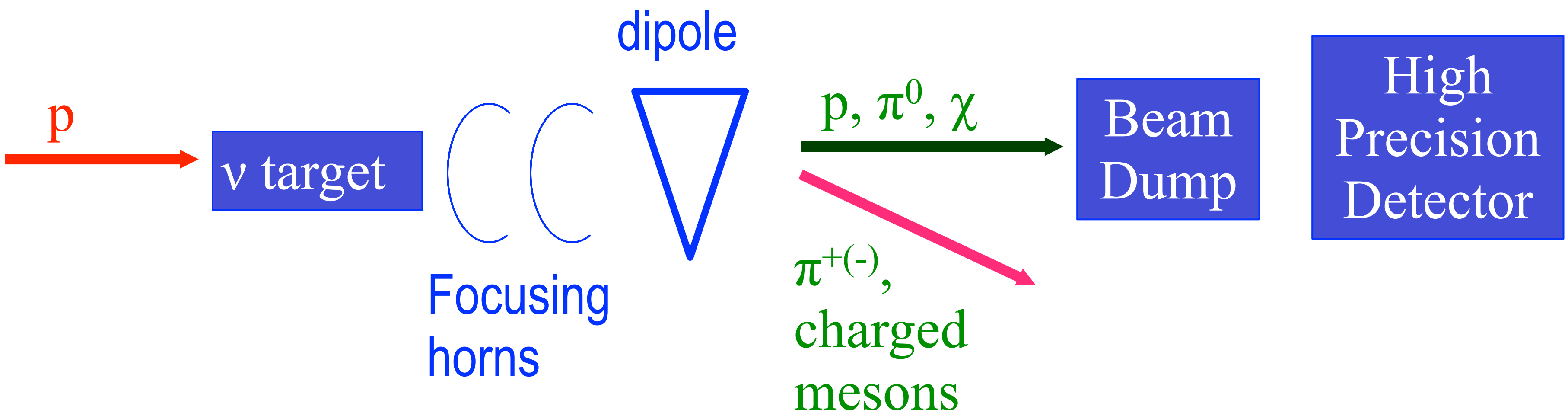

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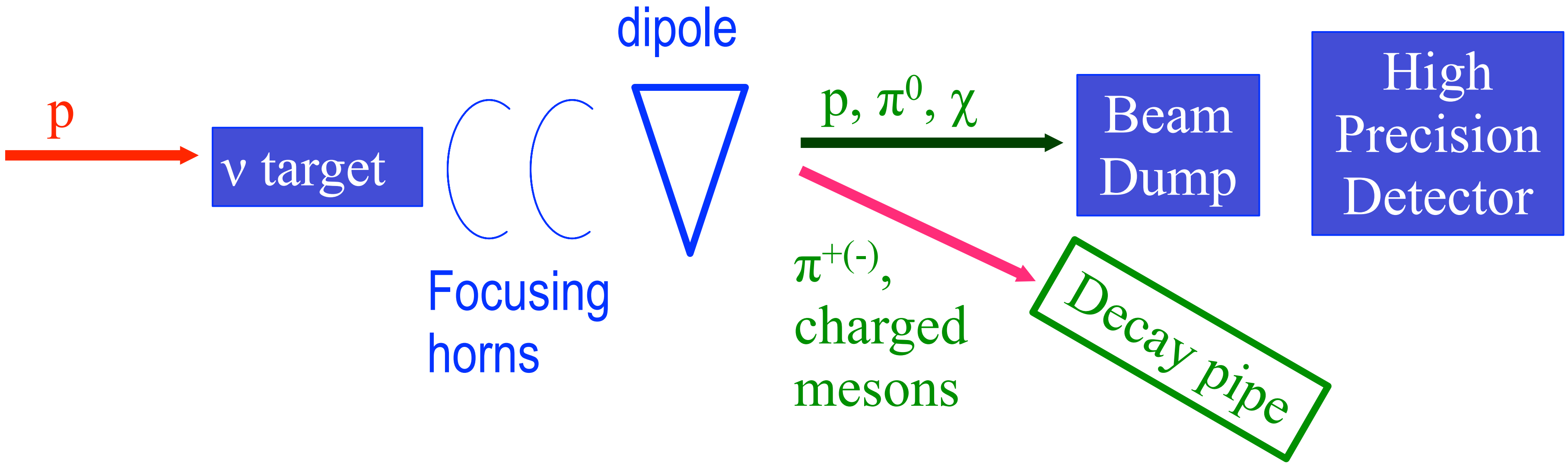

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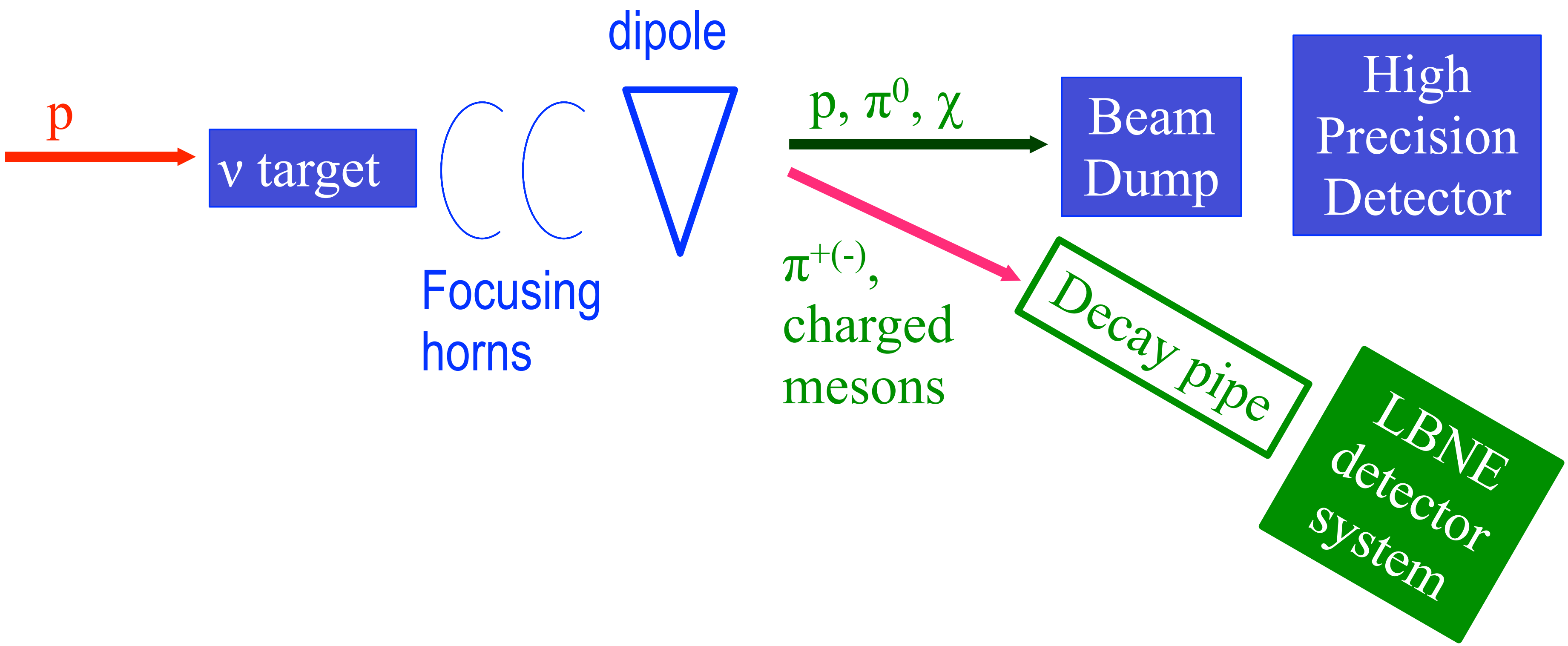

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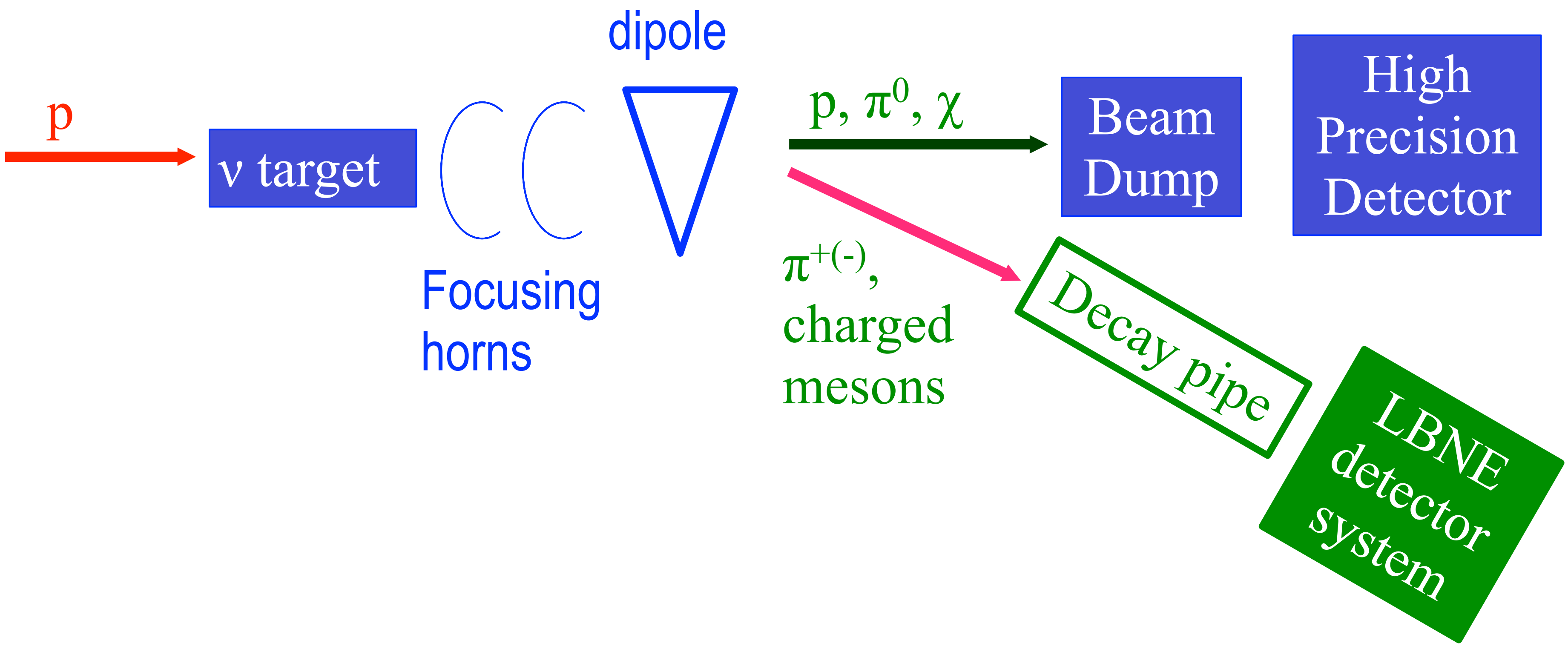
- Add a dipole after the mesons are fully focused with the 2nd horn



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- Perhaps we can think about DSHS?